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Stirling Laboratory Research Engine Survey Report

John W. Anderson
Frank W. Hoehn

September 15, 1979

National Aeronautics and
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Jet Propulsion Laboratory
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ABSTRACT

As one step in expanding the knowledge relative to and accelerating the development of Stirling engines, NASA, through the Jet Propulsion Laboratory (JPL), is sponsoring a program which will lead to a versatile Stirling Laboratory Research Engine (SLRE). An objective of this program is to lay the groundwork for a commercial version of this engine. It is important to consider, at an early stage in the engine's development, the needs of the potential users so that the SLRE can support the requirements of educators and researchers in academic, industrial, and government laboratories. For this reason, a survey has been performed, the results of which are described in this report.

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I. SUMMARY

A total of 57 responders expressed interest in acquiring some type of Stirling test engine; 45 believed that the SLRE could fulfill their specific technical requirements. Furthermore, 39 indicated that their budget might include funds which could be applied towards the purchase of such an engine. The academic community, however, listed acceptable cost as an important consideration for such a procurement. Several institutions indicated that a subsidy or some form of grant would be sought in order to permit acquisition of this type of equipment. Those responding from industrial and government laboratories, on the other hand, believe engine reliability to be the most important attribute for any test engine. This was followed, in order, by safety, versatility, performance and engine maintenance.

The predominance of university interest in an SLRE engine size smaller than 10KW can be attributed to two factors; first, its primary use as a teaching tool, and second, the expected lower cost of a smaller engine. Greater interest is shown in larger test engines by industrial and government laboratories, probably since their concerns include ground transportation and stationary power applications. Relative to the types of heat sources to be used, a slight preference for combustor heating was indicated, followed closely by electric, with solar heating a distant third.

In general, the potential high cycle efficiency and multi-fuel capability of the engine are listed as the most important characteristics for Stirling engines. These results undoubtedly reflect the growing concern for the conservation of petroleum-derived fuels. On an overall basis, there is widespread interest in the Stirling engine since it can fulfill a wide variety of potential roles. These roles are of course predicated on the successful development of commercially available engines in a variety of sizes. Composite ratings derived from the survey place air conditioning/refrigeration as the most promising use in both the near (1980-1990) term and far (>1990) term periods. Solar thermal electric energy conversion and surface transportation provide additional end-uses for Stirling cycle machines.

Approximately one-third of the 358 survey questionnaires were answered and returned with numerous comments. This response indicates the existence of significant interest within the technical community in Stirling engines and their potential uses.

II. INTRODUCTION

A. Survey Objectives

A survey of potential users of a Stirling research engine was initiated by the Liquid Propulsion and Engine Systems Section of the Control and Energy Conversion Division of the Jet Propulsion Laboratory in January of 1979, in an effort to determine the interests, needs and desires of those who are currently involved in heat engine research. The major objectives of the survey were:

1. To assess the current interest of the technical community in the Stirling engine and its potential uses.
2. To determine the extent of interest in a commercially available research engine.
3. For those interested in the laboratory engine concept, determine the key attributes desired.

With these objectives in mind, a questionnaire was prepared, and consisted of the following three basic sections.

Section A dealt with general information regarding the respondent and the organization represented, and also requested the submission of names of additional personnel within the organization who might also be interested in or involved with Stirling engine research.

Section B covered the goals and policies of the respondent's organization, and attempted to identify the intended uses of a Stirling research engine, assuming an acceptable model to be available within a size and cost range to be specified by the respondent.

Section C directly addressed the individual respondent, and involved personal opinion regarding special and/or desirable engine characteristics. Also in this section was a personal evaluation of the envisioned end uses of Stirling engines in both the near-term (1980-1990) and far-term (1990 and beyond) periods.

The final part of this section solicited unrestricted and uncategorized comments of any type which could aid in assessing overall questionnaire response.

B. Survey Participants

The names of potential participants were selected from a number of sources, all of which are listed in Appendix A of this report. In the academic category, schools and universities having established and recognized engineering departments were selected, but active involvement in Stirling teaching or research was not a prerequisite. Individuals within industry were chosen because of their known association with or interest in Stirling engine research or because of involvement with the study, development and/or manufacture of other types of heat engines. Also included were companies involved with energy, transportation, and the production of petroleum products.

Government-supported research laboratories and government agencies included those doing or managing research in energy (solar, atomic and fossil fuels), and transportation (naval, aviation and ground). Also included were potential applications in several forms of stationary power.

A master distribution list was compiled from the sources listed in Appendix A. When several names were given for a single organization, preference was given to those whose involvement with heat engines was known, followed by those who were identified as being in a supervisory or other decision-making role. Although the distribution list was made as inclusive as possible, it is likely, and regrettable, that some important names have been unintentionally omitted. The final tabulation was a list of 358 names representing a broad cross-section of the academic, industrial and governmental sectors within the United States and twelve foreign countries: Brazil, Canada, Iran, Israel, Japan, Mexico, Netherlands, Sweden, Switzerland, Taiwan, United Kingdom and West Germany. A list of the recipients by category and country is shown in Table I.

Table I. Survey Participants — Categories and Graphic Summary

Category	United States	Foreign Countries	Category Total
Academic	104	23	127
Industrial	152	18	170
Government	58	3	61
Total	314	44	358

The questionnaires, along with a cover letter, specification sheet, photograph and description of the JPL preprototype Stirling Laboratory Research Engine (SLRE), were mailed during a three week period starting January 10, 1979. The majority of the responses were received at JPL by March 1, 1979. A complete copy of the questionnaire is attached in Appendix E.

III. QUESTIONNAIRE REPLIES

A. Data Tabulation

The answers to each question or request for comment were tabulated as shown in Appendix B.

B. General Response to Survey

Table II shows the total number and percentage of questionnaires that were:

1. Mailed to potential participants in academic, industrial and governmental organizations;
2. Completed and returned to JPL by respondents in each of the three categories;
3. Returned as undeliverable.

The overall response of about one-third is considered significant and suggests that public interest exists in the Stirling engine project, and furthermore, lends credibility to the survey results.

Table II. Response to Survey

Category	Mailed No. (%)	Responded No. (%)	Undeliverable No. (%)
Academic	127 (35)	44 (35)	2 (1.6)
Industrial	170 (48)	58 (34)	3 (1.8)
Government	61 (17)	16 (26)	1 (1.6)
Totals	358 (100)	118 (33)	6 (1.7)

IV. SURVEY RESPONSE

In general, an attempt has been made to arrange the raw data given in Appendix B into related or significant groups, basically following the divisions used in the original questionnaire. Graphic presentations of these data and their relationships have been made wherever possible. In general, the bar chart or other graphic symbol quantities represent a percentage of the total involved, or a specific quantity of a known total number.

A. Responses to Specific Questions

1. General Interest

Response to Question A-4, "would you be interested in obtaining results of this questionnaire?" was nearly unanimous, with 93% of the total respondents from all categories (113 of 122) wishing to be apprised of the final survey results. In addition, 46 names were given in response to Question A-5, which requested the names of others within the respondents organization who might have an interest in the Stirling Laboratory Research Engine. These 46, when added to the original 358 to whom the questionnaire was sent, gives a total of 404 people who have a varying degree of interest in Stirling engines and associated research.

2. Goals and Policies

Questions B-1 through B-6 dealt with the goals and policies of the respondents organization, and were intended to define the present status of Stirling engine research and/or teaching within the organization. If an on-going program was non-existent, definition of future plans was requested. As can be seen in Figure 1, Question B-1, 36% or less of all organizations surveyed are now actively engaged in Stirling research, and of those not now involved, future research is contemplated by an average of slightly over 15%, as shown by Question B-2. It is encouraging to note, however, that in the academic category, Stirling cycle thermodynamics is being taught at 84% of the institutions surveyed. Also 43% of those not now offering such instruction plan to do so in the future, which may be an indication of expanding interest in the Stirling cycle, at least at the academic level. Of peripheral importance is the response to Question B-5, (Figure 2), showing that 96% of all academic institutions offer laboratory courses in the thermodynamics of heat engines.

Regarding Question B-6, on the ability to demonstrate performance, emissions and technology of Stirling engines, industry leads with a 62% capability. Government agencies and academic institutions are not far behind, with 53% and 44%, respectively. However, most such equipment is, in general, not specifically germane to Stirling engine testing, but could be used to demonstrate the given parameters on many types of heat engines. Thus, if a Stirling program were to be initiated at these locations, only a minimum expenditure might be necessary for special test equipment to perform the required testing that such a program would entail.

3. Desirable Characteristics

Question B-7 addresses six specific characteristics which are deemed desirable in a Stirling research engine. Included were safety, reliability, versatility, low maintenance, acceptable cost, and performance. Space was also provided in the questionnaire for the entry of other characteristics or attributes considered important by the respondent.

Respondents were requested to rank each of the listed characteristics on scale of 1 to 6, with 1 being of the highest rank. The answers are tabulated as shown in the raw data compilation, (Appendix B) and later reduced as shown in Table III.

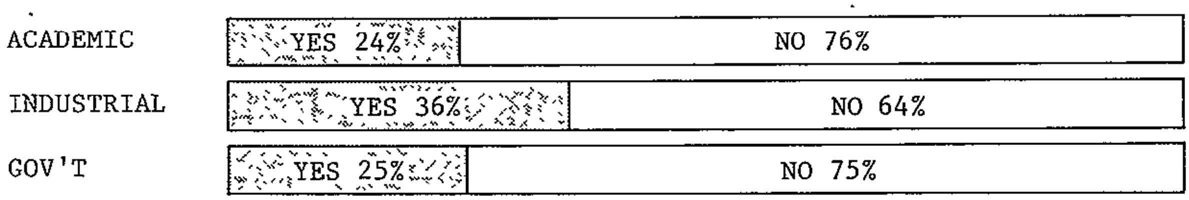
As can be seen in the raw data, overall ranking for any given characteristic ranged from 1 to 6, so a weighted value was assigned in numerical order to each number, 1 being worth 1, 2 worth 2, and so on up to 6. The responses for each number were counted, multiplied by its assigned value, and the sum total for all six numbers was derived. This sum was then divided by the total number of responses in that particular category. This was done in descending order, since a predominance of low numbers was indicative of high rank. As an example, under "Acceptable Cost," in the Academic category, the following results were obtained:

Rank No.	No. of Responses	Numerical Value
1	15	15
2	9	18
3	9	27
4	0	0
5	2	10
6	1	6
Totals	36	76

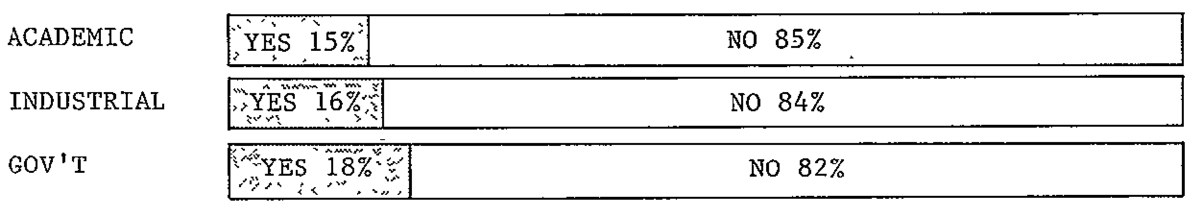
76/36 = 2.111

B. The questions below deal primarily with the goals and/or policies of your company, institution or organization.

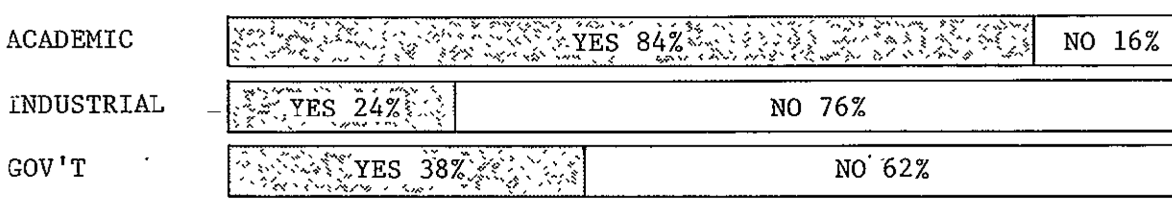
B-1. Does your organization have an on-going Stirling engine research program?



B-2. If not, is such a program planned for the future?



B-3. Does your institution teach or sponsor for employees courses which include the thermodynamics of the Stirling cycle engine?



B-4. If not, is such training or instruction anticipated for the future?

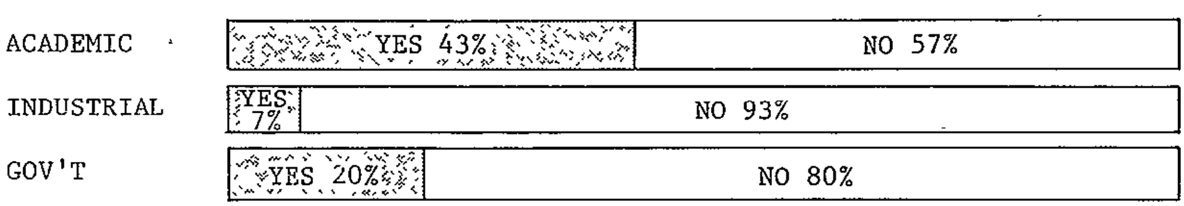
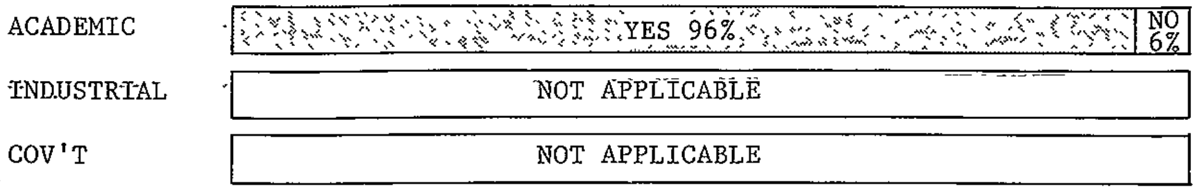


Figure 1. Organizational Goals and Policies

B-5. If a school or university, does your institution offer laboratory courses in the thermodynamics of heat engines?



B-6 Is your laboratory equipped to demonstrate the performance, emissions and technology of Stirling engines?

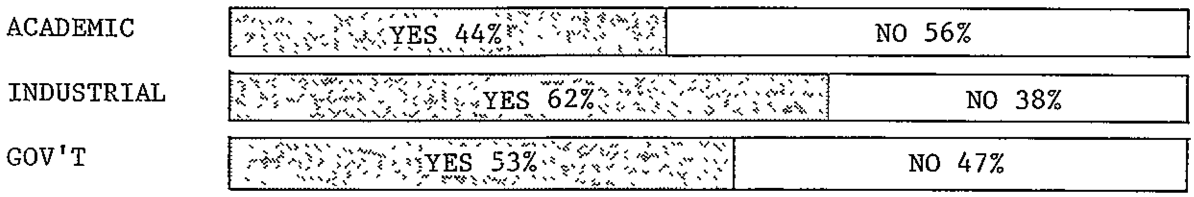


Figure 2. Organizational Goals and Policies (Continued)

B-7. In order that a Stirling engine of this type be used as a research and/or teaching tool, certain characteristics are desirable. Please rank the following attributes in the order of importance to you.

Desirable Characteristics	Ranking					
	Academic	Weighted Average	Industrial	Weighted Average	Gov't	Weighted Average
Cost	1	2.11	2	3.27	6	4.15
Safety	2	2.64	3	3.31	3	3.33
Versatility	3	2.81	4	3.45	4	3.75
Reliability	4	3.24	1	2.60	1	2.62
Performance	5	4.65	5	3.62	2	2.67
Maintenance	6	4.66	6	4.53	5	4.08

Table III. Desirable Engine Characteristics

This placed "acceptable cost" as the characteristic of primary importance in the Academic category, with the remaining 5 in descending order, as given in Table III.

The same order of placement was retained in Table III for the Industrial and Government Categories, even though this placed the rankings out of sequence. This actually serves to spotlight the wide range of opinion regarding important characteristics from one category to the next.

(a) Academic Category

Acceptable cost received first priority as a necessary consideration, and this is further borne out by additional comments (Appendix D) provided by several respondents. One such comment noted that the probable cost of such an engine and its installation would far exceed the institution's entire yearly budget for all instructional equipment. Several others suggested that a subsidy or some form of grant would be required, and be welcomed. Another suggested that basic research could be performed by government agencies, similar to what has been done in the past for the aviation industry through NACA and NASA.

Safety, versatility and reliability were rated in that order after acceptable cost. Performance and engine maintenance were farther down the list, (in 5th and 6th rank). This is understandable from an academic point of view, where teaching and experimentation are the primary objectives.

(b) Industrial Organizations

Reliability ranks first in this category, followed closely by cost, safety, versatility and performance. Maintenance was again ranked of least importance.

From an industrial point of view, this can be assumed as a normal response. The competitive nature of industry demands that sort of ranking, or at least an attempt to achieve it, even though the engine proposed in the survey is designed primarily as a laboratory research and development tool. It is also evident from added comments that many of the industrial respondents who have a positive attitude toward Stirling development are looking at the long-term effects of Stirling research. The assumption appears to be that from such research will evolve Stirling engines which will be competitive with (and perhaps superior to) the various types of engines in use today.

(c) Government Agencies

Reliability and performance were practically tied for the No. 1 position in this category, with safety, versatility and maintenance following in that order. Of lowest importance was cost, which probably evolves from an understanding of the nature of basic research in any area, in that development of any new idea or product is costly during the early stages of such development. Abundant examples could be cited; in the aviation, automotive, aerospace and pharmaceutical fields. However, the prime objective in all cases has been to develop a final product which would in the long run justify the developmental cost, and result in a product for which there would be a continuing and long-term demand or need. This could not be accomplished without the expenditure of adequate time, effort and money during the development period.

4. Suitability of the NASA/JPL Engine

Three responses, B-8, 9, and 10, were requested in this area, and the tabulation is shown graphically in Figure 3. A summation of all responses is given below the bar graph, showing actual numbers of responses as well as a percentage of the total that they represent.

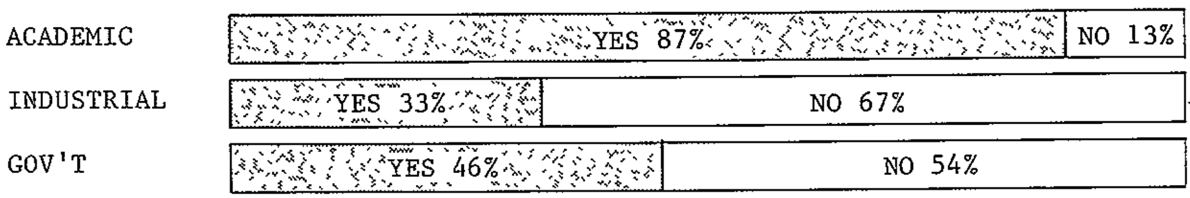
54% of all respondents expressed interest in acquiring some type of Stirling research engine, while 82% of the total in all categories felt that the NASA/JPL SLRE would fulfill their technical requirements. 56% stated that their budget could include the acquisition of such an engine. However, a clearer picture can be presented when the responses are again divided into the three specific categories.

(a) Academic Category

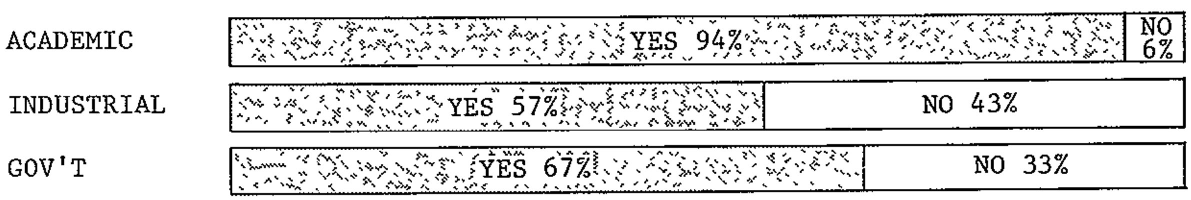
Of the 44 total academic respondents, 39 (89%) answered to Question B-8; of these, 34 (87%) expressed an interest in acquiring a Stirling research engine. Furthermore 34 (94%) stated that the NASA/JPL engine would meet their specific technical requirements, soundly confirming its acceptability to the academic field as a teaching and research tool.

However, in Question B-10, only 48% of the respondents indicated that their budget could include the purchase of such an engine. The need is obviously there, but the money certainly is not. This is further borne out in Question B-12 (Table IV), wherein 21 of 44 respondents (48%) indicated

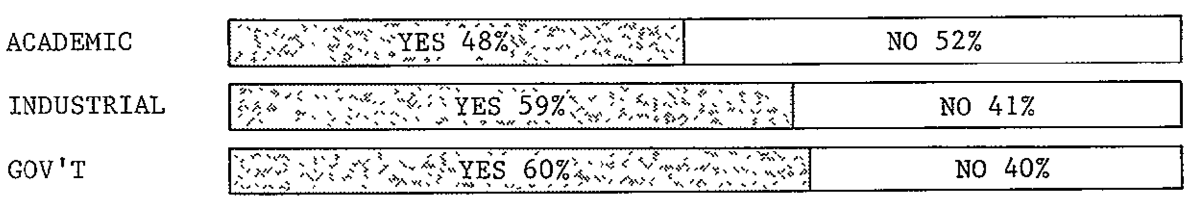
B-8. Would your institution be interested in acquiring a Stirling research engine, assuming its availability in a size class of interest?



B-9. If so, would the NASA/JPL engine described in the attachment satisfy the technical requirements of your institution?



B-10. If available, could your budget include acquisition of a Stirling research engine?



Question	Yes		No	
	No.	%	No.	%
B-8	57	54	48	46
B-9	45	82	10	18
B-10	39	56	31	44
Summary of All Responses				

Figure 3. Engine Acquisition, Suitability and Budgetary Limits

B-12. What is an approximate upper limit on acquisition cost that your institution might place on the engine described?				
Category	No. of Responses	Maximum (K$)	Minimum (K$)	Average (K$)
Academic	21	25	1	7.4
Industrial	16	100	2	40.1
Government	6	150	20	62.5

Table IV. Acquisition Cost Limit

the dollar amount representing their upper limit for the purchase of a research engine. Amounts varied from $1,000 to $25,000, resulting in an average of $7,400 from all responses. The maximum amount of $25,000 would probably not be sufficient to cover the overall cost of a NASA/JPL engine, further highlighting the need for grants or subsidies to academic institutions.

(b) Industrial Organizations

Again referring to Figure 3, 52 out of 59 (88%) answered question B-8 in this category. However, only 17 of 52 (33%) expressed interest in acquiring a Stirling engine. Of these, only 14 answered question B-9, and 8 of them, (57%) found the NASA/JPL engine to be acceptable. Reasons for this rather low level of acceptance (as compared to the academic area) were in many cases specifically stated in added remarks at the end of the questionnaire. Typical comments were related to (1) lack of multiple or interchangeable heat sources, (2) improper configuration and/or size, (3) insufficient provisions for instrumentation, and (4) research engines being too versatile, too expensive, and too sensitive to inexpert handling. Others expressed the negative view that the Stirling engine would never become sufficiently competitive with gasoline or Diesel engines, citing the 150 years since its inception, and its subsequent lack of development and/or commercialization as evidence.

However, many respondents expressed strongly positive opinions, and

cite lack of effort as a prime reason for slow development. These people feel that the Stirling engine is definitely worthy of a concentrated development effort, using the latest technological know-how, something which has been done on a very limited scale up to now.

As far as acquisition cost (question B-12, Table IV) is concerned, sixteen responses were received, and show a large variation in available or commitable funds, with a low of $2000 and a high of $100,000. The average of all responses was slightly over $40,000, which could indicate a positive commitment to Stirling research.

(c) Government Agencies

In this category, a total of sixteen questionnaires was returned, and on question B-8, 13 of 16 (81%) responded. About half (46%) expressed interest in acquiring a Stirling engine, and in question B-9, 67% said that the NASA/JPL engine would be an acceptable choice. Regarding budgetary status, (question B-10), 6 of 10 (60%) indicated that the cost of such an engine could be justified, generally within the next 1 to 3 years.

As far as the upper cost limit is concerned (Table IV), answers ranged from a low of $10,000 to a high of $150,000, resulting in an average of $62,500 among all respondents. This is in good agreement with the data given in question B-7, Table III, wherein cost was ranked in last place as an important attribute. However, the cost limits given are probably quite realistic, and may represent a clear understanding of what is involved in the acquisition of a Stirling research engine.

5. Engine Size, Usage and Heat Sources

These areas of interest were covered in questions B-13, 14, and 15, and the results are shown graphically in Figure 4, Table V and Figure 5, respectively.

(a) Academic Category

The predominance of interest in an engine size smaller than 10 Kw can probably be attributed to two factors; first, its primary use as a teaching tool, where larger size would be of minimum value, and second, the expected lower cost of a smaller engine. This tends to bear out the importance of the cost factor in the academic sector, as has already been discussed elsewhere in this report.

B-13. What engine size is of interest to your organization?

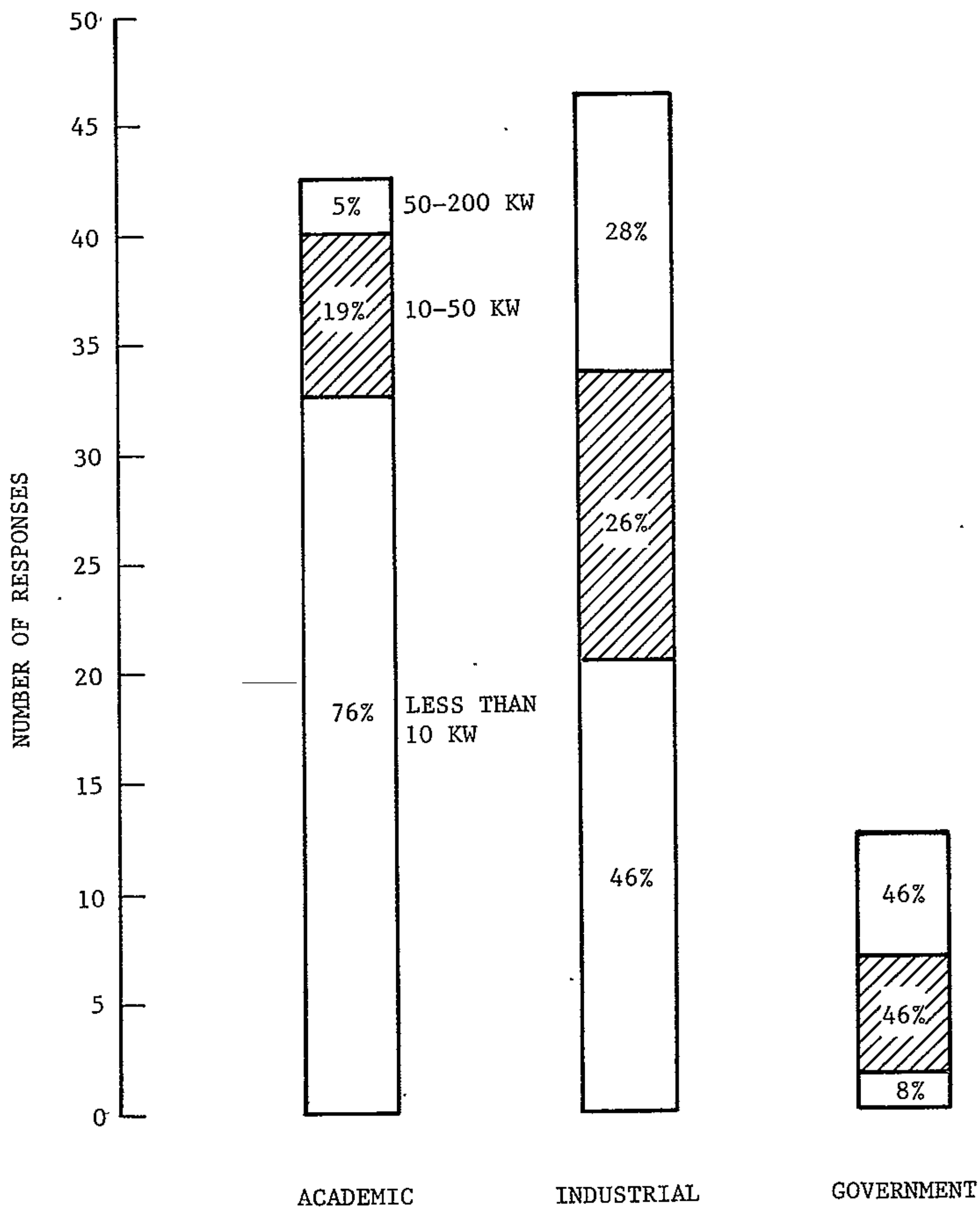


Figure 4. Preferred Engine Size

B-14. What uses of the SLRE would be of interest to your organization?			
SLRE Uses	Ranking		
	Academic	Industrial	Gov't
Teaching Aid	1	6	5
Demonstration	2	4	2
Analytical Models	3	3	3
Fuels Research	4	5	4
Systems Development	5	2	1
Component Development	6	1	1

Table V. Research Engine Usage

Regarding question B-14, intended organizational uses of the Stirling engine, Table V shows that in the academic field, its use as a teaching aid and demonstration device rank above the other four categories, all of which are much lower but quite close as a group. This could be interpreted to indicate that, as would be expected, teaching is of prime importance, while research and development are in a secondary role.

As to types of heat sources to be used, question B-14 shows a slight favoring of combustor heating, followed by electric and solar sources, in that order. What Figure 5 does not show is that many of the respondents indicated the ability to use all three types of heat source. With the significant interest shown in solar power (24%), this could be a positive indication of growing concern for the conservation of fossil fuels, and could lead to the eventual commercialization of solar-powered Stirling generators.

(b) Industrial Category

The engine size of greatest interest in this area is also the less than 10 Kw, although the percentage is much lower (46% vs 76%) than for the academic field. The remaining 54% of industrial respondents are almost

B-15. What types of heat sources could be used to power a research engine in your laboratory?

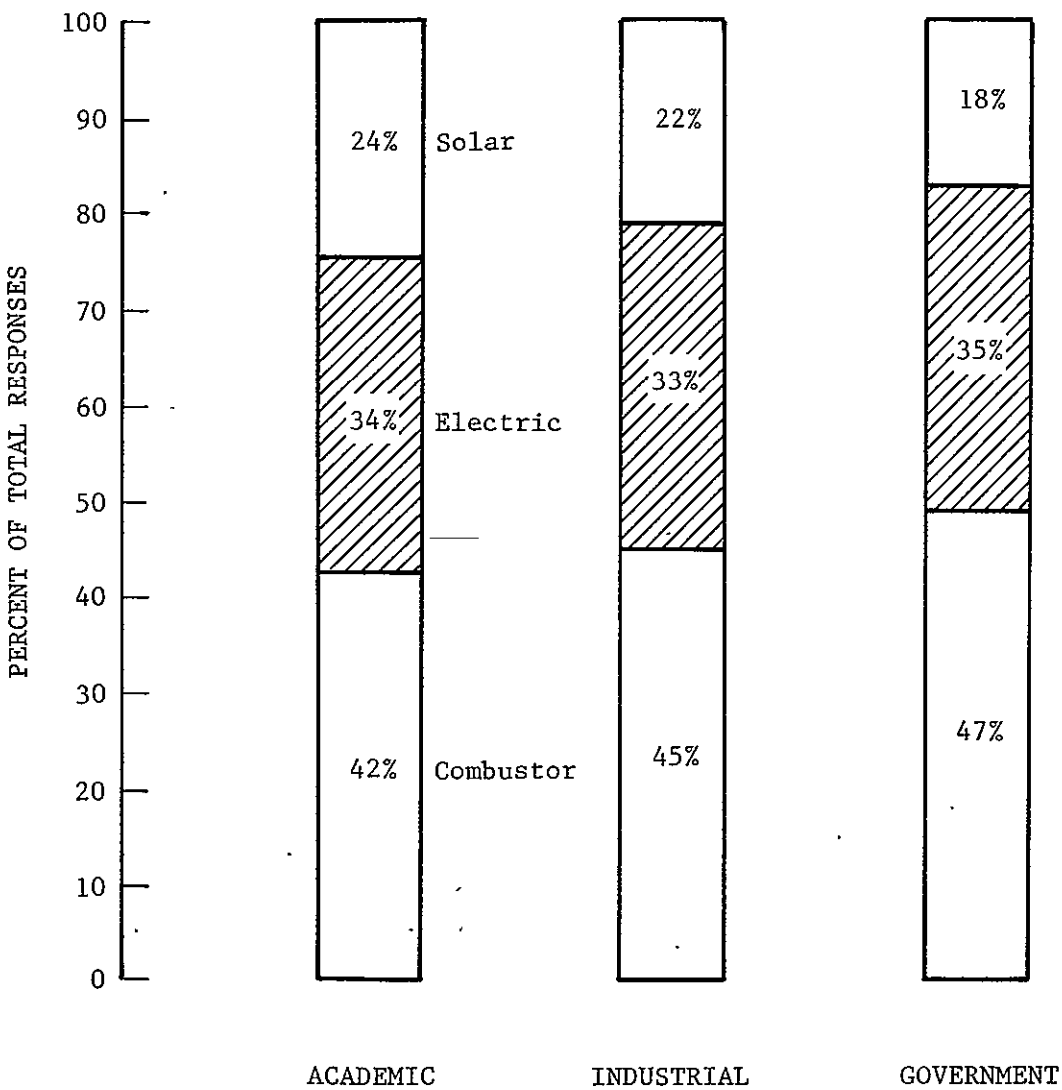


Figure 5. Available Heat Sources

equally divided between the 10 to 50 Kw and the 50 to 200 Kw sizes (26% and 28%, respectively). This may be an indication of industry desire to eventually provide product availability to a majority of potential users, but to perform basic research and development more economically using the smaller (under 50 Kw) engine size. Interest in the larger sizes could also reflect potential use in automotive and stationary power applications.

Answers to question B-14 produced the results shown in Table VI, with systems and component development leading the field by a considerable margin. Third most important was use of the engine in support of analytical models, with demonstration, fuels research and teaching aid far down the scale.

Heat sources to be used or which are planned do not differ appreciably from those given for the academic category, with nearly half (45%) having combustor capability, and 33% equipped for or favoring electrical power. Solar power again was third, with 22% having such an interest.

(c) Government Agencies.

In this category, larger engines were preferred by a large majority, with 46% each favoring the 10 to 50 Kw and the 50 to 200 Kw sizes. The remaining 8% expressed interest in the under 10 Kw category. This could possibly be due to the orientation of governmental research centers toward research and development for mass consumption, rather than for individual or small-scale use.

Regarding intended uses for the engine, the governmental and industrial categories are nearly identical (see Table V), with system and component development of first and equal ranking. Next come demonstration and analytical models, with fuels research and teaching aid near the bottom. This ranking provides no real surprises, and appears to be consistent with the overall research and development function assigned to such government-supported centers.

In question B-15 (Figure 5), planned heat sources do not vary to any major extent from the academic and industrial categories, with combustor being the primary source at 47% followed by electric at 35%, and solar coming in last with 18%. 41% indicated that more than one heat source could be used.

C. The questions below are directed more to you as a professional individual than as a representative of an organization.

C-1. What special characteristics of Stirling engines do you expect to find most advantageous for end-use?			
Desirable End-Use Characteristics	Ranking		
	Academic	Industrial	Gov't
High Thermal Efficiency	1	2	1
Multi-Fuel Capability	2	1	2
Low Emissions	3	4	4
Low Noise Levels	4	3	3

Table VI. Special End-Use Characteristics

6. <u>Special Characteristics and End Uses</u>

This segment of the questionnaire contains three questions (C-1, -2 and -3) which involve the personal and professional opinion of the individual respondent, which may not necessarily be the same as those of his organization. Question C-1 deals with special or desirable Stirling engine characteristics which would be advantageous for end use, while C-2 and C-3 deal with potential end uses in the near term (1980-1990) and far term (beyond 1990) periods. Results from question C-1 are shown in Table VI, while those from C-2 and C-3 are combined in Table VII for better comparison.

(a) Academic Category

The special characteristic (question C-1) which ranked first in this category was high thermal efficiency, closely followed by multi-fuel capability and low emissions, with low noise levels a rather distant fourth. These results may reflect a knowledge of certain inherent characteristics of the Stirling engine, or may be an indication of a growing concern for fuel conservation, and also with concern for the ecological impact of fuel-burning engines.

C-2. What end uses for Stirling engines do you expect to become commercially viable in the near (1980-1990) term?

C-3. What end uses for Stirling engines do you expect to become viable beyond 1990?

End Use	Ranking					
	1980 - 1990			Beyond 1990		
	Academic	Industrial	Gov't	Academic	Industrial	Gov't
Air Conditioning and Refrigeration	1	1	3	2	1	2
Solar to Electric Energy Conversion	2	3	2	2	2	1
Surface Transportation	2	3	4	1	3	2
Other*	3	2	1	4	5	1
Underground Propulsion	4	4	5	3	4	3

*See Text for explanation and details.

Table VII. Commercially Viable End Uses, Near and Far Term

As for Stirling engine end uses in the near term, air conditioning/refrigeration ranked in first place, closely followed in a tie for second place by solar/electric-energy conversion and surface transportation. Third place went to the "other" category, and the suggested uses were for auxiliary power/electrical generation, water pumping and irrigation, and for unspecified uses in the mining industry. Finally, in fourth position was Stirling use in underground (mining) propulsion.

The picture changes when predictions beyond 1990 are given. Surface transportation becomes number 1, with air conditioning/refrigeration and solar/electric conversion tied for second place. Third spot goes to underground propulsion, and the "other" category is fourth. In the last category,

uses most frequently mentioned were auxiliary power/electrical generation, stationary power and mining operations.

(b) Industrial Category

Industrial respondents rated multi-fuel capability to be of primary importance in question C-1, while high thermal efficiency, low noise levels, and low emissions followed in that order. The percentage difference between ratings of the listed characteristics is not large, which could indicate that all of the four are considered important in the overall picture.

In the near-term end use question, air conditioning/refrigeration was ranked No. 1, the same as in the academic area. However, in No. 2 place was the "other" category. Respondents were generous and innovative with their own suggestions, with portable power, auxiliary power generation, stationary power, and water pumping/irrigation most frequently mentioned. Third place went to solar/electric energy conversion and surface transportation (a tie) while underground propulsion was fourth.

Far-term uses were somewhat rearranged, although air conditioning/refrigeration, solar/electric conversion and surface transportation were in 1-2-3 order. Fourth was underground propulsion, with "other" uses (auxiliary power and electrical generation) in fifth place.

(c) Government Agencies

Special characteristics ratings by this group did not differ greatly from those in the academic or industrial fields. High thermal efficiency was rated as most important, followed by multi-fuel capability, low noise levels, and low emissions in that order.

Near-term end uses in the "other" category were the most numerous with auxiliary power/electrical generation, and cogeneration being the most frequently mentioned. Also included were water and irrigation pumping, and stationary power use. The remaining four in order of rank were solar/electric energy conversion, air conditioning refrigeration, surface transportation, and underground propulsion.

For the far-term period, "other" uses retained first place, but shared it with solar/electric energy conversion. Uses in the "other"

category were practically a repeat of those described for the near-term period. In addition, underwater propulsion was also given as a possible use. Second place was also a tie, between surface transportation and air conditioning/refrigeration. Third place went to underground propulsion.

(d) Engine End Use Summary

Some rather interesting and viable conclusions are possible based on the data from questions C-2 and C-3.

On an overall basis, there is widespread general interest in the Stirling engine, plus a sizable number of qualified people who feel that it can fulfill a wide variety of potential roles. These roles are of course predicated on the successful development of a competitive engine in a variety of sizes.

Composite ratings derived from all three responding categories place air conditioning/refrigeration as the most probable use in both the near and far term periods. Solar electric energy conversion and surface transportation are not far behind, in second and third place, respectively.

Many innovative uses not specified in the questionnaire were suggested by respondents in all categories. These uses, which have been previously described, would require or could make use of a variety of engine sizes and heat sources.

Interest in and attention to solar energy as a heat source is widespread, and it is frequently suggested as a viable and perhaps necessary alternative to fossil fuels, especially petroleum products.

V. SURVEY CONCLUSIONS

A. Significant Points

The data received from the 118 participants in the survey was compiled and categorized, and the following statements and conclusions are made based upon an analysis of that data.

1. The overall response to the survey was more then 1/3, and represents a significant interest in the NASA/JPL engine concept, and in Stirling engine research in general. With few exceptions, the questionnaires were returned fully answered, with additional comments included

wherever appropriate. Over 90% of those who responded are interested in receiving the reported results of this survey, and this is seen as a further indication of continuing interest in Stirling research and development.

2. The concept of developing a commercially available Stirling Laboratory Research Engine was well accepted by a majority of all respondents. A total of 57 institutions have been identified as being interested in acquiring some type of Stirling research engine. The largest response was received from the academic community, which also expressed concern for the ultimate procurement cost. Respondents from several universities suggested that a Federal grant might be appropriate to assist in the acquisition of a laboratory test engine.

3. A total of 45 respondents indicated that the NASA/JPL engine could fulfill their specific technical requirements for a test engine. In making additional comments, some respondents feel that the expanded effort in research and development made possible by the use of such a test engine will help overcome many of the technical problems faced in the development of the Stirling cycle engine. Some specific problems encountered in recent development programs were related to seals, high temperature materials, analytical computer models, control systems and engine accessory equipment. The engine technology and understanding of the thermodynamic cycle which can result from the use of this Stirling Laboratory Research Engine should be applicable, but not limited to, a study of all these problem areas.

4. The engine described in the questionnaire represents a preprototype version which is not necessarily representative of a fully developed or optimized Stirling cycle machine. Results of this survey, relative to usable heat sources and engine size, for example, can impact the design of the industry-produced, commercial version of the Stirling Laboratory Research Engine.

5. Potential uses of the Stirling engine and its near-term and far-term applications are numerous, with many respondents giving innovative suggestions for additional uses. Significant application includes air conditioning/refrigeration systems for the next decade and beyond.

Ground transportation systems are envisioned as being important users of Stirling engines in the 1990's. Additional uses include large stationary power applications, underwater propulsion systems, and for water pumping in agricultural irrigation systems.

6. The Stirling engine is seen as a candidate heat engine for the conversion of solar energy to electrical power. This stems primarily from its high cycle efficiency and external heat source capability, and the importance of this aspect should grow as the fossil fuel problem becomes more critical.

VI. QUESTIONNAIRE SUMMARY

The following is a summary of the answers given in the questionnaire in terms of the total number of positive responses.

	Academic	Industrial	Government
Type of organization represented by the respondent.	44	61	17
Those willing to be identified in published reports	36	42	12
Have expressed interest in receiving copy of report on survey.	41	56	16
Identified others in organization who are interested in Stirling research	18	18	10
Number of organizations identified as having an ongoing Stirling engine research program.	10	20	5
Organizations planning such a program for the future.	4	6	2
Number of institutions which teach or sponsor courses on thermodynamics of Stirling engines.	35	12	6
Institutions planning such training for the future.	2	3	3

	Academic	Industrial	Government
Number of schools or universities which offer lab courses in thermodynamics of heat engines.	38	N/A	N/A
Laboratories which are equipped to demonstrate performance, emissions and technology of Stirling engines.	17	27	9
Number of institutions interested in acquiring a Stirling research engine.	35	17	7
Organizations whose technical requirements would be satisfied by the NASA/JPL engine.	33	8	5
Organizations whose budget could include the acquisition of a Stirling research engine.	11	23	5
Uses of the SLRE which would be of interest to the respondents organization			
(a) Teaching aid	36	3	1
(b) Component development	14	25	9
(c) Analytical models	18	13	6
(d) Demonstration	25	8	6
(e) Systems Development	16	24	8
(f) Fuels Research	16	7	3
(g) Other	5	7	1
Heat sources which could be used to power a research engine			
(a) Solar	21	15	3
(b) Electric	30	23	6
(c) Combustor	37	32	9
(d) Other	4	8	4

	Academic	Industrial	Government
Special Stirling engine characteristics which are found to be most advantageous for end use			
(a) High thermal efficiency	30	42	12
(b) Low emissions	24	29	5
(c) Low noise levels	15	33	6
(d) Multi-fuel capability	26	43	10
(e) Other	6	11	2
Stirling engine end uses expected to become commercially viable from 1980–1990			
(a) Solar/electric conversion	16	8	6
(b) Automotive use	10	5	2
(c) Other surface transport	6	7	2
(d) Underground propulsion	8	11	2
(e) Air Cond/Refrigeration	20	36	5
(f) Other	9	23	8
End uses expected to become viable beyond 1990			
(a) Solar/electric conversion	23	31	7
(b) Ground transport	28	29	6
(c) Underground Propulsion	12	16	4
(d) Air Cond/Refrigeration	22	32	6
(e) Other	10	14	7
Number of respondents who submitted additional comments	15	34	10

APPENDIX A

SOURCES FOR DISTRIBUTION LIST

1. "Automotive Engineering" (SAE); Roster Issue, March 1978.
2. "Stirling Engine Newsletter", name and address list provided by Prof. W. Martini.
3. "Automotive Technology Status & Projections", JPL Publication 78-71. (External distribution list).
4. Fourth International Symposium on Automotive Propulsion Systems; NATO/CCMS, April 17-22, 1977 (Attendance list).
5. "Stirling Engine Design Manual", NASA CR-135382, April 1978, Directory Listing.
6. Personal contacts.

APPENDIX B

TABULATION OF SPECIFIC RESPONSES TO SURVEY QUESTIONNAIRE

Academic Institutions

Identification Number	Identify in Reports	Want Report Results	Others Interested	Have Ongoing Stirling Research	Such Research Planned?	Employee Courses	Employee Courses Planned	Lab Courses in Your School	Lab Equipped for Demo., etc.	Stirling Engine Attributes in Order of Importance: Acceptable Cost	Low Maintenance	Performance	Reliability	Safety	Versatility	Other
A-1	N	Y	Y	N	N	Y		Y	N	3	4	6	1	5	2	
A-2	N	N	N	N	N	Y	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2	1	3	
A-3	Y	Y	Y	N	?	Y		Y	Y	1	6	5	3	2	2	
A-4	Y	Y	N	N	N	Y		Y	N	1	2	5	3	1	4	
A-5	Y	Y	N	N	N	Y		Y	Y	6	4	5	1	3	1	
A-6	Y	Y	N	N	N	Y		Y	Y	1			3	2		
A-7	Y	Y	Y	N	N	Y		Y	Y	2	4	6	3	5	1	
A-8	N	Y	Y	N	N	Y		Y		2	2	3	2	1	2	
A-9	Y	Y	N	N	?	Y		Y	Y	3	5	4	2	1	6	
A-10	Y	Y	Y	N	Y	Y		Y		5	6	4	1	5	2	
A-11	Y	Y	N	N		Y		Y	Y	1	6	4	5	3	2	
A-12	N	Y	N	N	N	Y		Y	Y	2	3		4	1		
A-13	Y	Y	N	N	N	N	N	Y	Y	1	5	6	3	2	4	
A-14	Y	Y	N	N	N	Y		Y	N	2	6	5	4	3	1	
A-15	Y	Y	N	N	N	Y		Y	N	1	5	6	4	3	2	
A-16	Y	Y	Y	N	N	Y		Y	N	1	4	6	2	5	3	
A-17	Y	Y	N	Y		Y		Y	N	3					1	2
A-18	Y	Y	Y	N	N	Y		Y	N	1	5	4	2	6	3	
A-19	Y	Y	N	N	Y	Y		Y	N	1	5	2	4	6	3	
A-20	Y	Y	Y	N	Y	N	Y	Y	N				1	2	3	
A-21	Y	Y	N	N	N	N	N	Y	Y	2	6	5	3	4	1	
A-22	Y	Y	Y	N	N	Y		Y	N	3	5	6	4	1	2	
A-23	Y	Y	N	N		Y		Y	N	2				1	3	

Academic Institutions (Contd)

Identification Number	Identify in Reports	Want Report Results	Others Interested	Have Ongoing Stirling Research	Such Research Planned?	Employee Courses	Employee Courses Planned	Lab Courses in Your School	Lab Equipped for Demo. etc.	Stirling-Engine Attributes in Order of Importance: Acceptable Cost	Low Maintenance	Performance	Reliability	Safety	Versatility	Other
A-24	Y	Y	Y	N	Y	N	Y	Y	N	2	4	6	3	1	5	
A-25	Y	Y	N	N	N	Y		Y	Y	1	6	5	4	3	2	
A-26	Y	Y	N	Y		Y		N	Y	3	6	4	5	1	2	
A-27	Y	Y	Y	Y		N	N	Y	N	1	6	5	4	3	2	
A-28	N	Y	Y	N	N	Y	Y	Y	Y	X	X		X			
A-29	N	Y	N	Y		Y		Y	Y	3	4	5	2	1	6	
A-30	Y	Y	N	Y		N	N	N	N							
A-31	Y	Y	N	Y		Y		Y	N	1	3	2	4	5	6	
A-32	Y	Y	Y	N	N	Y		Y	N	1	6	4	5	3	2	
A-33	Y	Y	N	Y		Y		N		3	4	1	6	2	5	
A-34	Y	Y	Y	Y		Y		Y	Y	2	5	6	4	1	3	X
A-35	Y	Y	N	N	?	Y		Y	N	3	4	6	5	1	2	
A-36	Y	Y	Y	Y		Y		Y	Y	X		X				
A-37	Y	Y	Y	N	N	N		Y	N	X	X		X			
A-38	Y	Y	N	N	N	Y		Y	N	2	5	6	4	1	3	
A-39	Y	Y	N	N	?	Y		Y	Y	1				3	2	
A-40	Y	Y	Y	Y		Y		Y	Y	1	3	2	5	6	4	
A-41	(No answers; comment only)															
A-42	Y	Y	Y	N	N	Y	–	Y	N						1	
A-43	(No answers; comment only)															
A-44	Y	Y	N	N	N	Y	–	Y	N	3	6	4	2	1	5	

Academic Institutions (Contd)

Identification Number	Plan to Acquire Engine?	NASA/JPL Engine OK?	Budget Include Engine?	What Fiscal Year	Upper Cost Limit, K	Engine Size, kW	Uses Planned for Stirling Engine: Analytical Model	Component Development	Demonstration	Fuels Research	Systems Development	Teaching Aid	Other	Heat Source Planned: Solar	Electric	Combustor	Other
A-1	Y	Y	?	?	?	<10					X	X			X		
A-2	N	Y	N	?	10	50-200						X		X	X	X	
A-3	Y	Y	?	?	?	10 50	X		X			X			X	X	
A-4	Y	Y			Need Grant	<10			X			X	X		X	X	X
A-5	Y	Y			2	<10			X		X	X		X	X	X	
A-6	Y	N	?		?	<10			X			X		X	X		
A-7	Y	Y	Y	80	?	<10	X	X	X		X	X		X	X	X	
A-8	Y	Y	?	?	?	<10		X				X			X	X	
A-9	Y	Y	?	?	1	<10	X			X	X	X				X	
A-10	Y	Y	N		5	<10	X		X	X		X		X		X	
A-11	Y	Y	Y	80	25	<10			X			X			X	X	
A-12	?	?	?	—	15	<25		X	X			X			X	X	
A-13	Y	Y	?		10	<10		X	X	X		X		X	X	X	
A-14	Y	Y	?	?	?	<10	X		X	X	X	X		X	X	X	
A-15	Y	Y	?	?	?	<10		X	X	X		X		X	X	X	
A-16	Y	Y			?	<10	X		X			X		X	X	X	X
A-17	Y	Y	N			10-50							X		X	X	
A-18	Y	Y	Y	81	3	10-50			X			X		X	X	X	
A-19	Y	Y	Y	81	3	<10	X					X	X	X		X	
A-20	Y	Y	Y	81	3	<10		X	X	X		X		X	X	X	
A-21	Y	Y	?	?	5	<10				X	X	X		X	X	X	
A-22	?	—	N		10	<10			X	X		X			X	X	
A-23	Y	Y	Y	79-80	1	<10			X			X				X	
A-24	Y	Y	Y	80-81	?	<10	X		X		X	X			X	X	
A-25	Y	Y	?	?	?	10-50		X		X	X	X				X	

Academic Institutions (Contd)

Identification Number	Plan to Acquire Engine?	NASA/JPL Engine OK?	Budget Include Engine?	What Fiscal Year	Upper Cost Limit, K	Engine Size, kW	Uses Planned for Stirling Engine: Analytical Model	Component Development	Demonstration	Fuels Research	Systems Development	Teaching Aid	Other	Heat Source Planned: Solar	Electric	Combustor	Other
A-26	Y	Y	N			<10					X		X		X		
A-27	N	N				<10	X	X	X					X	X	X	X
A-28	Y	Y	?	?	10	<10	X			X		X			X	X	
A-29	N		N			<10				X		X				X	
A-30	N																
A-31	Y	N	N	Gift OK	1	<10			X		X	X		X	X	X	
A-32	?	?	N		5	50-200	X		X	X		X	X			X	
A-33	N		N			10-50	2	1			4	3					X
A-34	Y	Y	Y	80	10	<10	X	X	X	X	X	X			X	X	
A-35	Y	Y	Y	80+	5	<10	X					X		X	X	X	
A-36	Y	Y	Y	80	1	<10					X			X		X	
A-37	Y	Y	N			<10		X								X	
A-38	Y	Y	N			<10	X	X	X	X	X	X		X	X	X	
A-39	Y	Y	N		?	<10 & 10-50	X							X	X	X	
A-40	Y	Y	?	?	15	10-50	X	X	X	X	X	X		X		X	
A-41	(No answers; comment only)																
A-42	Y	Y	?	?	?	<10	X	X	X		X	X		X	X	X	
A-43	(No answers, letter only)																
A-44	Y	Y	Y	–	10-15	<10			X	X		X			X	X	

Academic Institutions (Contd)

Identification Number	Special End Use Features					Expected Near-Term End Uses (1980-1990)						Expected End Uses After 1990				
	High Thermal Efficiency	Low Emissions	Low Noise Levels	Multi-Fuel Capability	Other	Solar/Electric Conversion	Automotive Use	Other Surface Transport	Underground Propulsion	Air Cond & Refrig	Other	Solar-Electric Conversion	Ground Transport	Underground Propulsion	Air Cond & Refrig	Other
A-1	X					X				X		X			X	
A-2					X											
A-3	X	X		X		X	X					X	X		X	
A-4	X	X	X	X							X	X	X		X	
A-5	4	2	3	1		X		X			X		X			X
A-6	X					X						X				
A-7	X	X	X	X	X		X			X			X		X	
A-8	X	X	X	X												
A-9	X	X		X			X			X			X		X	
A-10	X	X		X		X			X			X	X	X	X	
A-11	X									X			X			
A-12		X		X		X			X	X		X	X	X	X	
A-13	X	X		X												
A-14				X				X					X			
A-15		X		X		X				X			X			
A-16	X		X				X		X			X				
A-17	X										X					X
A-18					X	X				X		X	X		X	
A-19	X	X	X	X							X	X				X
A-20	X	X		X		X				X		X	X		X	
A-21		X		X							X	X	X		X	
A-22		X											X	X		
A-23										X						
A-24	X	X		X			X	X		X		X	X	X	X	
A-25	X	X	X			X				X		X	X		X	

Academic Institutions (Contd)

Identification Number	Special End Use Features					Expected Near-Term End Uses (1980-1990)						Expected End Uses After 1990				
	High Thermal Efficiency	Low Emissions	Low Noise Levels	Multi-Fuel Capability	Other	Solar-Electric Conversion	Automotive Use	Other Surface Transport	Underground Propulsion	Air Cond & Refrig	Other	Solar/Electric Conversion	Ground Transport	Underground Propulsion	Air Cond & Refrig	Other
A-26						X				X			X			X
A-27	X								X		X	X	X	X	X	X
A-28	X	X	X	X						X		X	X	X	X	
A-29	X	X	X	X												
A-30							X			X	X		X			X
A-31	X			X		X	X	X	X	X		X	X	X	X	
A-32	X	X	X	X								X			X	
A-33	2	3	4	1	X	X			X		X		X		X	
A-34	2	3	4	1	5	X	X	X	X	X	X	X	X	X	X	X
A-35	X					X				X			X	X		
A-36	X			X		X	X					X	X			
A-37			X	X						X					X	
A-38	X											X	X	X	X	X
A-39												X				
A-40	X	X		X			X		X	X		X	X	X	X	X
A-41		(No answers; comment only)														
A-42	X	X	X	X	(Depends on cost relative to alternatives)											
A-43		(No answers; letters only)														
A-44	X	X	X	X				X		X		X	X	X	X	X

Industrial Facilities (Contd)

Identification Number	Identify in Reports	Want Report Results	Others Interested	Have Ongoing Stirling Research	Such Research Planned?	Employee Courses	Employee Courses Planned	Lab Courses in Your School	Lab Equipped for Demo, etc.	Stirling Engine Attributes in Order of Importance						
										Acceptable Cost	Low Maintenance	Performance	Reliability	Safety	Versatility	Other
I-1	Y	Y	N	N	N	N	N									
I-2	N	Y	N	N	N	N	N								X	X
I-3	N	N	Y	Y	Y	N	N			2	5	1	3	6	4	
I-4	Y	Y	N	Y	Y	N	N	N	N	3	1		2			X
I-5	N	N	N	N	N	N	N	N	N	3	2	6	1	5	4	
I-6	Y	Y	Y	Y		N	Y		Y	5	4	3	2	1	4	
I-7	Y	Y	Y	Y	Y				Y				X			
I-8	Y	Y	N	N	N	N	N	Y	Y	X	X	X	X			
I-9	Y	Y	N	Y		Y			Y	7	6	5	4	1	2	3
I-10	N	Y	Y	N	N				Y	1	2	3	2	2	4	
I-11	Y	Y	N	Y		N	N	N	N					X	X	
I-12	Y	Y	N	N	N	N		N		2	4	2	3	5	6	1
I-13	Y	Y	N	N	N	N		Y		3	5	6	4	2	1	
I-14	N	Y	N	Y					N	1	5	3	4	6	2	
I-15	Y	Y	N	N	N	N	N		Y	1			2	3	4	
I-16	N	Y	N	N	Y	Y			N	X		X			X	
I-17	Y	Y	Y	N		N	N		N						X	X
I-18	Y	Y	N	N	N	N		Y								
I-19	N	Y	N	N					Y							
I-20	Y	Y	N	N	N	Y				1	5	3	2	6	4	
I-21	Y	N	N	N	N	N	N		Y	4	3	2	1			
I-22	Y	Y	N	N	N	N	N		Y	6	4	1	3	2	5	
I-23	Y	Y	N	Y		Y			Y	5	4	6	3	2	1	
I-24	Y	Y	N	N	N	N	N		Y	1	5	2	3	6	4	
I-25	Y	Y	N	N	N	N	N		N	2	5	1	3	4	6	

Industrial Facilities (Contd)

Identification Number	Identify in Reports	Want Report Results	Others Interested	Have Ongoing Stirling Research	Such Research Planned?	Employee Courses	Employee Courses Planned	Lab Courses in Your School	Lab Equipped for Demo, etc.	Stirling-Engine Attributes in Order of Importance: Acceptable Cost	Low Maintenance	Performance	Reliability	Safety	Versatility	Other
I-26	Y	Y	Y	Y		N	N	Y	N	1	6	5	4	3	2	
I-27	Y	Y	N	N	N	N	N		Y	3	4	1	5	2	6	7
I-28	N	Y	Y													
I-29	N	Y		Y		N	N		Y	3	6	2	4	1	5	
I-30	Y	Y	N	Y		N	N		Y	6	4	3	2	5	1	
I-31	Y	Y	N	N	N	N	N	N	Y	4	6	5	1	3	2	
I-32	Y	Y	N	N	N	N	N		Y	6	5	2	3	4	1	
I-33	Y	Y	N	N	N	N	N		Y	5	3	6	2	4	1	
I-34	Y	Y	Y	Y		Y	N		Y	5	6	2	4	3	1	
I-35	Y	Y	Y	Y		Y			Y			X	X		X	X
I-36	Y	Y	N	Y		Y		N		3	4	7	6	2	5	X
I-37	Y	Y	N	Y		N	N	N	N	4	6	7	3	5	2	X
I-38	Y	Y	N	N	N	Y			Y	2	5	6	1	4	3	
I-39	Y	Y	Y	Y		N	N		Y	3	2	5	1	4	6	
I-40	Y	Y	N	N	N	N	N		N							
I-41	Y	Y	N	Y		N	N	N	Y						X	X
I-42	Y	Y	Y	N	N	N	N	N	N	3	4		2	1		X
I-43	Y	Y	Y	N	Y	N	N		Y	5	6	1	3	4	2	X
I-44	N	Y	N	Y		N	N	N	N						X	
I-45	Y	Y	Y	N	Y	N	Y		N	5	4	3	1	2	6	
I-46	N	N	N	N	N	Y			N	6	3	4	2	1	5	
I-47	N	Y	Y	N	N	N	N		Y	3	5	4	2	1	6	
I-48	N	Y	N	N	N											
I-49	Y	Y	N	N	N	N	N		Y	2	3	6	4	1	5	
I-50	N	Y	N	N		Y			N	4	6	1	2	5	3	

Industrial Facilities (Contd)

Identification Number	Identify in Reports	Want Report Results	Others Interested	Have Ongoing Stirling Research	Such Research Planned?	Employee Courses	Employee Courses Planned	Lab Courses in Your School	Lab Equipped for Demo, etc.	Stirling Engine Attributes in Order of Importance						
										Acceptable Cost	Low Maintenance	Performance	Reliability	Safety	Versatility	Other
I-51	Y	Y	N	Y		Y			N	2	6	7	3	5	4	1
I-52	Y	Y	N	N	–	–	–	–	Y	6	5	2	1	4	3	
I-53	Y	Y	Y	N	Y	N	N	–	N	2	6	4	5	1	3	
I-54	Y	Y	N	Y	–	–	–	–	Y	4	5	6	1	3	2	
I-55	N	Y	N	N	N	Y	–	–	Y	4	5	3	1	6	2	
I-56	–	Y	–	(Letter only; no answers)												
I-57	Y	Y	Y	N	Y	N	N	–	N	1	6	5	3	4	2	
I-58	Y	Y	N	N	N	N	N	–	–	2		3	1			X

Industrial Facilities (Contd)

							Uses Planned for Stirling Engine							Heat Source Planned			
Identification Number	Plan to Acquire Engine?	NASA/JPL Engine OK?	Budget Include Engine?	What Fiscal Yr	Upper Cost Limit, K	Engine Size, kW	Analytical Model	Component Development	Demonstration	Fuels Research	Systems Development	Teaching Aid	Other	Solar	Electric	Combustor	Other
I-1	N																
I-2	N					<10		X	X								
I-3	N		N			<10							X				
I-4	Y	N	N			<10					X		X				X
I-5	N	N	N														
I-6	Y	Y	Y	80		<10	X	X			X					X	
I-7	Y	N	Y		100	<10								X	X	X	X
I-8	N	N	N													X	
I-9	Y					<10	X	X						X	X	X	
I-10	N					50-200											
I-11									X					X			
I-12	Y	N	Y	79-80	?	50-200	X							X	X		
I-13	Y	?	Y	*	40	50-200				X			X				
I-14	N					<10									X	X	
I-15	N	N	N		2	10-50			X		X				X	X	
I-16	N					<10		X			X			X	X	X	
I-17	N	?	Y	As Reqd	?	50-200	X	X		X	X		X	X	X		
I-18	N	N	N														
I-19	Y	Y	Y	80-81	25	<10 & 10-50		X								X	
I-20	Y	1	Y	82	25	50-200			X		X			X	X	X	
I-21	N		Y		50	None		X			X			X	X		
I-22	N		Y	80+	10-100	50-200			X						X	X	
I-23	Y	?	Y	80	50	10-50	X	X		X	X				X	X	
I-24	Y	N	Y	80+	10	<10 & 10-50					X					X	
I-25	N					50-200					X						

Industrial Facilities (Contd)

Identification Number	Plan to Acquire Engine?	NASA/JPL Engine OK?	Budget Include Engine?	What Fiscal Yr	Upper Cost Limit, K	Engine Size, kW	Uses Planned for Stirling Engine: Analytical Model	Component Development	Demonstration	Fuels Research	Systems Development	Teaching Aid	Other	Heat Source Planned: Solar	Electric	Combustor	Other
I-26	N	N				<10								X	X	X	X
I-27	Y	Y	Y	82	10	50-200		X								X	
I-28																	
I-29	N	N	N			10-50& 50-200										X	X
I-30	N		N														
I-31	N	?	N	N	?	10-50& 50-200		X			X					X	
I-32	N		Y	Any	100	10-50				X	X					X	
I-33	N							X							X	X	
I-34	N		Y			<10	X	X	X		X	X		X	X	X	X
I-35	N					10-50 & 50-200	X	X							X	X	
I-36	N		N			50-200	2	1			4	3					X
I-37	N																
I-38	N	Y	?	?	5	<10		X			X			X	X	X	
I-39	Y	Y	Y	80	?	<10		X							X		
I-40	N																
I-41	Y	N	Y			<10							X	X		X	
I-42	Y	N	Y			<10		X			X		X	X		X	X
I-43	Y	?	Y	79	?		X	X			X				X	X	
I-44	N	Y	Y			10-50		X								X	
I-45	Y	N	Y	79-80	50	<10		X	X		X			X			X
I-46	N		Y														
I-47	Y	Y	N			<10 & 10-50									X		
I-48	N		Y	Any													
I-49	N																
I-50	N																

Industrial Facilities (Contd)

Identification Number	Plan to Acquire Engine?	NASA/JPL Engine OK?	Budget Include Engine?	What Fiscal Yr	Upper Cost Limit, K	Engine Size, kW	Uses Planned for Stirling Engine							Heat Source Planned			
							Analytical Model	Component Development	Demonstration	Fuels Research	Systems Development	Teaching Aid	Other	Solar	Electric	Combustor	Other
I-51	N	N				<10			X			X	X		X		
I-52		N				50-200	X	X		X	X					X	
I-53	N	N	N	?	–	10-50	X	X								X	
I-54				?	50	All	X	X							X	X	
I-55	N	–	N	–	–	10-50	X	X		X	X				X	X	
I-56		(Letter only; questionnaire not returned)															
I-57	N	–	–	–	–	–					X			X	X	X	
I-58	N	–	N	–		>1000					X						

Industrial Facilities (Contd)

Identification Number	Special End Use Features: High Thermal Efficiency	Low Emissions	Low Noise Levels	Multi-Fuel Capability	Other	Expected Near-Term End Uses (1980-1990): Solar/Elect Conversion	Automotive Use	Other Surface Transport	Underground Propulsion	Air Cond & Refrig	Other	Expected End Uses After 1990: Solar-Elect Conversion	Ground Transport	Underground Propulsion	Air Cond & Refrig	Other
I-1	X		X								X	X	X		X	
I-2	X		X		X						X					
I-3	X			X			X			X					X	
I-4			X	X		X				X						
I-5				X						X					X	
I-6	X	X	X							X			X		X	
I-7	X			X		X				X			X	X		
I-8	X	X	X	X		X						X				
I-9	X	X		X		X				X						X
I-10	X	X	X								X		X	X		
I-11	X	X	X	X		X				X		X			X	
I-12	X	X	X		X	X					X	X	X			
I-13	X			X		X				X		X		X	X	
I-14			X	X	X					X	X	X	X			
I-15	X	X							X	X		X	X	X	X	
I-16	X	X	X	X								?	?	?	?	
I-17				X		X										
I-18						X					X				X	
I-19	X	X	X	X	X					X	X				X	X
I-20	X	X							X	X		X	X	X	X	
I-21	X			X											X	X
I-22		X	X	X				X	X	X		X		X	X	
I-23	X	X	X	X		X			X	X	X		X		X	
I-24	X	X	X	X		X			X	X	X	X	X	X	X	X
I-25	X			X								X	X		X	

Industrial Facilities (Contd)

Identification Number	Special End Use Features					Expected Near-Term End Uses (1980-1990)						Expected End-Uses After 1990				
	High Thermal Efficiency	Low Emissions	Low Noise Levels	Multi-Fuel Capability	Other	Solar/Elect Conversion	Automotive Use	Other Surface Transport	Underground Propulsion	Air Cond & Refrig	Other	Solar/Elect Conversion	Ground Transport	Under Ground Propulsion	Air Cond & Refrig	Other
I-26	X								X		X	X	X	X	X	X
I-27	X			X					X			X			X	
I-28																
I-29	X	X	X	X		X				X	X	X	X		X	X
I-30				X		X						X		X		
I-31	X	X	X	X			3	2	1			X	X	X	X	X
I-32	X									X	X	X				
I-33	X		X	X				X		X		X		X	X	
I-34	X	X	X	X	X			X		X	X	X	X	X	X	X
I-35	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
I-36	2	3	4	1	X	X			X		X		X		X	
I-37	1	3	4	2	5					X	X		X			
I-38			X	X				X		X		X	X			
I-39	X										X				X	
I-40																
I-41	X	X	X			X	X				X	X				
I-42	X	X		X	X	X				X	X	X	X		X	X
I-43	X	X	X	X		?			?	X		?	X	?	X	X
I-44				X						X		X			X	
I-45	X					X	X			X			X	X		
I-46	1	2	3	4								X	X		X	
I-47	X		X	X							X					X
I-48				X												
I-49			X							X	X				X	X
I-50	X	X	X	X							X	X	X		X	

Industrial Facilities (Contd)

Identification Number	Special End Use Features: High Thermal Efficiency	Low Emissions	Low Noise Levels	Multi-Fuel Capability	Other	Expected Near-Term End Uses (1980-1990): Solar-Elect Conversion	Automotive Use	Other Surface Transport	Under Ground Propulsion	Air Cond & Refrig	Other	Expected End Uses After 1990: Solar-Elect Conversion	Ground Transport	Under Ground Propulsion	Air Cond & Refrig	Other
I-51	1	3	4	2				X		X		X	X			
I-52	X	X	X	X						X						
I-53			X	X	X				X	X				X	X	
I-54	X	X	X	X	X					X		X	X	X		
I-55				X						X	X	X			X	X
I-56																
I-57	X			X						X	X	X	X			
I-58		X		X						X			X			

Government Agencies

Identification Number	Identify in Reports	Want Report Results	Others Interested	Have Ongoing Stirling Research	Such Research Planned?	Employee Courses	Employee Courses Planned	Lab Courses in Your School	Lab Equipped For Demo, etc.	Stirling Engine Attributes in Order of Importance						
										Acceptable Cost	Low Maintenance	Performance	Reliability	Safety	Versatility	Other
G-1	Y	Y	N	N		N			N			X		X	X	
G-2	Y	Y	N	N	N	N	N		Y	2	4	1	3	5	6	
G-3	N	Y	N	N	N	N	Y		N	5	6	2	3	4	1	
G-4	N	Y	Y	Y		Y			Y	4	6	2	3	1	5	
G-5	N			N	N	N	N		N							
G-6	Y	Y	Y	N	N	Y			Y	3	5	2	4	6	1	
G-7	N	Y	N	N	N	Y			Y	5	3	2	1	4	6	
G-8	Y	Y	Y	N	Y	Y	Y		N	4	3	5	1	2	6	
G-9	Y	Y	Y	N	N	Y			Y	5	4	1	3	6	2	
G-10	Y	Y	Y	N	Y	N	N		Y	4	2	3	1	5	7	6
G-11	Y	Y	Y	Y		N	N			5	4	2	6	3	1	
G-12	Y	Y	N	Y		N	N		Y	3	2		1			
G-13	N	Y	N	N	N	N	N	Y	N	4	3	6	2	1	5	
G-14	Y	Y	N	Y		Y		Y	Y	4	6	5	3	1	2	
G-15	Y	Y	Y	N	N	N	N	–	N	6	5	1	3	2	4	
G-16	Y	Y	Y	N	N	N	N	–	N	–	–	–	–	–	–	

Government Agencies (Contd)

Identification Number	Plan to Acquire Engine?	NASA/JPL Engine OK?	Budget Include Engine?	What Fiscal Yr	Upper Cost Limit, K	Engine Size, kW	Uses Planned for Stirling Engine							Heat Source Planned			
							Analytical Model	Component Development	Demonstration	Fuels Research	Systems Development	Teaching Aid	Other	Solar	Electric	Combustor	Other
G-1	?	?	?	81	100	<200		X			X			X		X	
G-2	?	?	?	?	?	50-200		X	X		X			X	X	X	
G-3	Y	N	Y	81	25	<200			X		X	X		X	X		
G-4	Y	Y	?	?	50	<200	X	X	X	X	X				X	X	
G-5	N																
G-6	?	?	Y	?	30	10-50		X			X						X
G-7	N		N														
G-8	Y	Y	Y	80	None 10 units	50-200	X		X								X
G-9	Y	?	Y	80-82	Need Table	50-200	X	X	X		X				X	X	X
G-10	Y	Y	Y	ASAP	20	10-50 & to 1000		X		X	X		X		X	X	
G-11	N		N			500-3000 H.P.											
G-12	N	N	N			100-500										X	X
G-13	N																
G-14	Y	Y	Y	80-81	150	10-50	X	X							X	X	
G-15	N					10-50	X	X	X	X	X						
G-16	N		N			50-200	←				None						→

Government Agencies (Contd)

Identification Number	Special End Use Features					Expected Near-Term End Uses (1980-1990)						Expected End Uses After 1990				
	High Thermal Efficiency	Low Emissions	Low Noise Levels	Multi-Fuel Capability	Other	Solar/Elect Conversion	Automotive Use	Other Surface Transport	Underground Propulsion	Air Cond & Refrig	Other	Solar-Elect Conversion	Ground Transport	Underground Propulsion	Air Cond & Refrig	Other
G-1	X				X	X					X					
G-2	X				X	X										
G-3	X			X						X	X	X	X	X	X	X
G-4	X	X	X	X		X	X	X								
G-5																
G-6			X	X							X					
G-7	X	X														X
G-8	X				X	X	X	X				X	X			
G-9	X		X	X						X	X					X
G-10	X		X	X		X				X	X		X			
G-11				X							X					X
G-12					X						X				X	
G-13	X			X							X	X	X			X
G-14	X	X	X	X		X			X	X		X		X	X	
G-15	X	X							X	X		X	X	X	X	X
G-16				X								X			X	X

APPENDIX C

SLRE SURVEY

Summary of Responses in "Other" Categories

Question B-14. What uses of the SLRE would be of interest to your organization? If "other", please explain:(1)

A-4(2)	Performance testing
A-17	Development of improved models for internal sub-processes, especially in cylinders
A-19	Research on Stirling engine
A-26	Expand hydraulic Stirling engine technology to higher performance levels
A-32	Research on subsystems, e.g., heat exchangers
I-3	Heat pump prime mover
I-4	Research and development for 12-volt electric generator
I-13	Lubricant additives
I-17	Applications research
I-41	D.C. electrical power generation
I-42	Energy conversion; multi-fuel D.C. power generation for unattended computers and communication equipment
I-51	As a basis for educational unit
G-10	Life test evaluation

(1) Specific options listed for this question were: teaching aid, component development, analytical models, demonstration, systems development and fuels research.

(2) Number identifies survey participant, coded to preserve anonymity of respondent.

APPENDIX C

Question B-15. What types of heat sources could be used to power a research engine in your laboratory? If "other", please explain:[3]

A-4	Perhaps steam
A-16	Reject heat
A-27	Stored thermal energy
A-33	Heat battery
I-4	Wood
I-7	Heat pipe
I-26	Stored thermal energy
I-29	Diesel engine exhaust heat
I-34	Fluidized bed, radioisotope, metal combustion, heat storage
I-36	Heat battery
I-42	Radioactive isotope
I-45	Reuse of process thermal energy and use of exothermic reaction energy
G-7	Nuclear heat source
G-8	Thermal storage unit, up to 200,000 Btu's
G-9	Latent heat storage device
G-12	Radioisotope

[3] Heat sources listed for this question were: solar, electric and combustor.

APPENDIX C

Question C-1. What special characteristics of Stirling engines do you expect to find most advantageous for end-use? If "other", please describe:(4)

A-2	I really don't expect to see them used commercially.
A-7	Low lubricating oil consumption and degradation
A-18	New thermal cycle
A-26	All of above, plus reliability, depending on specific end use.
A-33	Use of heat battery
A-34	Regenerative braking for vehicles.
I-2	Compactness
I-12	Ability to operate from concentrated solar energy.
I-14	Long life
I-19	Use of rejected heat
I-34	Long service life, scaleability, configuration flexibility
I-35	Multi-heat source (solar)
I-36	Use of heat battery
I-37	High part load efficiency
I-42	Simplicity and reliability
I-53	Possibly high reliability, if this proves to be valid.
I-54	It is not one particular characteristic, but the combination in a single engine that makes it most attractive
G-8	Ability to charge the thermal storage unit electrically, which is a way to reduce the demand upon petroleum products.
G-12	Capability of running for years continuously without any maintenance

(4) Special characteristics listed for this question were: high thermal efficiency, low emissions, low noise levels and multi-fuel capability.

Question C-2. What end uses for Stirling engines do you expect to become commercially viable in the near (1980-1990) term? If "other", please describe:[5]

A-4	Limited specialized applications
A-5	Electrical generation for remote and under-developed countries and areas.
A-17	None based on current research programs which are trying to get end results with minimum fundamental foundations
A-19	Power for pumps in agriculture and ranches
A-21	I seriously doubt that any of the above will be commercially viable before 1990.
A-27	Auxiliary electric power where low noise and convenience are important
A-30	Power source for remote locations
A-33	Underwater
A-34	Mining industry - appropriate technology
I-1	Marine electrical generators
I-10	Special low power engines - up to ten horsepower - with emphasis on low noise
I-12	Auxiliary power unit
I-14	General purpose portable power - farm, construction, etc.
I-18	Solar powered generator
I-19	Dispersed cogeneration
I-23	Stationary power and total energy systems
I-24	Industrial applications of all types, if cost of manufacture were similar to an equal horsepower Diesel engine

(5) Specific near term end uses listed for this question were: solar to electric conversion, automotive use, other surface transportation, underground propulsion, and air conditioning and refrigeration.

APPENDIX C

I-26	Auxiliary electrical power
I-29	Fuel powered electric generator
I-32	Low horsepower/weight and volume, steady speed and load uses, e.g., small generator sets, pumping, etc.
I-34	General industrial; power generation
I-35	Dispersed power generation using non-scarce fuel
I-36	Underwater
I-37	Stationary power generation
I-41	Multi-fueled generating sets
I-42	Cogeneration of AC/DC power in distributed power systems (e.g., home sized electric generators, associated with furnaces; small prime movers and unattended water pumps)
I-47	Industrial
I-49	Auxiliary power plant on boats, trailers or motor homes
I-50	No real commercial use seen in that time scale
I-55	Stationary power
G-1	Probably none
G-3	Low technology water pumping
G-6	Stationary power
G-9	Standby power
G-10	Diesel replacement
G-11	Small dispersed generating plants burning coal
G-12	Power source for navigation aids, weather stations, and communications repeaters
G-13	Military and special purposes

APPENDIX C

Question C-3. What end uses for Stirling engines do you expect to become viable beyond 1990? If "other", please describe:[6]

A-5	Perhaps automotive, if it is cost competitive
A-17	Applications will depend on the nature of the advances made in engine technology
A-19	Power, including electrical generation, for areas with none available
A-26	Artificial heat power source
A-27	Auxiliary electric power where low noise and convenience are important
A-30	Power source for remote locations
A-34	Mining industry and other appropriate technology
A-38	Any or all of the above, assuming basic problems are solved
A-40	Electric power generation from fossil fuels
I-2	Underwater propulsion
I-9	Large Stirling engines for cogeneration; hybrid automotive engines
I-19	Dispersed cogeneration
I-24	Industrial application if cost of manufacture is competitive with Diesel engine
I-26	Auxiliary electric power
I-29	Operation of mobile machinery or equipment where low noise or low emissions are desirable
I-34	Dispersed power, general industrial, direct combustion of coal
I-42	Hybrid propulsion systems for industrial robots and material handling systems

[6] Specific end uses beyond 1990 were: solar to electrical energy conversion, ground transportation propulsion, underground propulsion, and air conditioning/refrigeration.

APPENDIX C

I-43	Power generation
I-47	Industrial
I-49	Auxiliary power plants on boats, trailers or motor homes
I-55	Stationary power
G-1	Stationary power plants
G-3	Irrigation
G-9	Underwater
G-11	Large coal-burning engines, competing with Diesels
G-13	Stationary standby power

APPENDIX D

STIRLING LABORATORY RESEARCH ENGINE QUESTIONNAIRE

Comments from Respondents
Academic Institutions

Code Number[1]	
A-1	"My comments reflect a design viewpoint separate and distinct from mechanical engineering. If you have not directed an inquiry to others in the Mechanical Engineering Department, you should do so."
A-3	"I feel that the Stirling engine with its inherent superiority in thermal efficiency and its versatility in power use has greater potential for future development than almost any other current movers that we are using today."
A-9	"The engine described looks like it is a good typical research engine; however for better teaching or for looking at something that would be suitable for mobile use, it needs to be configured for under-hood installation."
A-11	"Considerable government funding will be required to subsidize the manufacture and distribution of these engines. Possibly a grant program could provide an initial distribution of 50 engines to the most worth-while applicants."
A-12	"1. Performance curves would have been helpful in providing an accurate response. 2. Reliability data would also be helpful. 3. The university might consider a loan agreement whereby the engine would be available for demonstration purposes to local industry in JPL marketing efforts."

[1] Number identifies survey participant, coded to maintain anonymity of respondent.

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Code Number

A-16 "From the standpoint of the universities, the primary need is for a Stirling cycle engine for instructional and research purposes (e.g., similar to the role played by the CFR engines). If Stirling cycle technology is to be advanced, then graduates with knowledge, experience, and interest in such engines are required. Although we have had Stirling engines in our instructional laboratories, their design has been far removed from a realistic engine and instrumentation minimal. As a consequence we no longer include their demonstration in our instruction.

Since installed cost will probably be in the range of $50-100 K this becomes a major problem (our entire instructional equipment budget for a faculty of 45 is about $35K per year). Such facilities are acquired through purchase on research grants or, very occasionally, through special funds for instructional equipment. It is unlikely, that given discretion over the spending of this amount of money for instructional equipment, we would invest it in a Stirling engine facility. If there is a serious interest in getting such engines into university instructional programs, then some consideration must be given to how they might be provided to the ten to twenty largest heat engine instructional programs in the country at some modest fraction of their actual cost."

A-17 "I hope that JPL will use its influence to direct some small part of the large Stirling engine funds from the large 'quick end result' programs to some diversity of basic studies of Stirling problems. It is my opinion that the programs will benefit significantly from an improved fundamental analysis and additional basic engineering data."

A-27 "In undergraduate engineering education most professors will mention Stirling only in passing. I have offered my services several times with no response. Some enthusiasts will fire up a model Stirling engine. Possibly a few at this stage would have a lab experiment like

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the Leybold-Heraeus engine. If even 20% of the automobiles use Stirling engines, the picture would change, of course. Then every mechanical engineer would run a laboratory experiment on an instrumented automobile Stirling engine.

In graduate education or in special undergraduate projects by enthusiasts, the students will build their own machines by converting existing parts that are available at low cost.

The engine manufacturer will first start by tracking the development as many are doing now. Next they may hire a consultant and/or contact those firms already in the business. Obviously, the manufacturer will be looking for a profitable product. He will do as little basic engineering and design work himself as possible if it can be purchased elsewhere.

This leaves the contract research organizations. If they could sell a program that would allow them to buy a demountable research engine like the JPL machine for the purpose of measuring, correlating and publishing basic heat transfer and fluid flow data for heat exchangers and regenerators in the unique environment of a Stirling engine, they of course would do so. There are a lot of different possibilities and even with a wide open machine the instrumentation is not easy since no additional dead volume can be added. A number of laboratories might be funded to do this basic engineering for the benefit of the Stirling engine industry just like basic measurements on airfoils and such funded by the government have benefitted the aviation industry."

A-29 "Make a comprehensive review and critical evaluation of the work done by Ford Motor Co., United Stirling of Sweden, and Phillips Labs. Publish this in a report and follow it by your questionnaire."

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Code Number	
A-33	"I am active as an engineering consultant in underwater application of the Stirling engine, and as an adjunct professor teaching the subject 'Continuous Combustion Engines,' mainly Stirling engines. The university could very well make use of an experimental and research engine. Funding such an engine is the problem."
A-34	"Multi-fuel capability is the essence for industrial use-particularly the use of low grade coal and coal oil.
A-41	"I guess I have to conclude that when all else fails then try to sell it to the schools!" [sic]

APPENDIX D

Industrial Organizations

Code Number	
I-1	"Our product requires [engines having] low specific weight and bulk (high specific output) and rapid response."
I-2	"I regard as important in a research engine the capability to at least demonstrate operation with a number of potential heat sources, including fossil fuel combustion with air, closed chemical heat sources, and stored heat sources. Admittedly, this is to some extent separable from the closed cycle engine proper, but the effective integration of heat source and engine is an area as much in need of research as any other. Limitation to electrical heating makes the [JPL] system too obviously separated from "the real world." To what extent can different seal arrangements be used and tested in the visualized engine? For instance, can piston rod seals as well as crankshaft seals be tested?"
I-4	"If a loose tolerance Stirling in the 1/2-1 HP range were developed, it could use waste heat currently used as home heating fuels." [sic]
I-8	"Forget the Stirling for automotive applications."
I-9	"In regards to the technical requirements, I would be interested in higher dead volume ratios, since they are more consistent with present Stirling engine designs. Also, I feel that the mean pressure level of 68 ATM is too low."
I-10	"Presently conducted NASA programs are expected to clarify the competitive potential for Stirling engines in mass production. The main reasons are: High thermal efficiency and low emissions. Reasonable cost, high reliability, low fuel consumption, and low maintenance are considered to be the main problem areas."
I-14	"To us, the SLRE would not be useful. Our efforts would be directed toward a <u>specific configuration and size</u>-very few of our questions could be answered with the SLRE."

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Code Number	
I-15	"I believe that not enough attention is being given the problem of strategic materials requirements for Stirling engines. The need for cobalt and chromium will severely limit the economic viability of Stirling engines for the temperature range above about 1350°F (732°C) unless new alloys are developed and shown to be acceptable."
I-17	". . . will undertake technology assessment, system development, or test and evaluation programs for clients needing our services. We do anticipate possible work in this (Stirling) area, especially in solar energy conversion. Our laboratories are fully equipped to utilize an engine such as described, for these various purposes. The nature of our business is such, however as to preclude definitive statements of need in the absence of a specific support contract."
I-18	"I am interested in the Stirling engine as a solar power generator. There is no current work at my company in regenerative heat engines. Hope you are successful in your efforts to focus R&D on your engines. I think the Vuilleumier area is as important as Stirling, but neglected. Feel free to contact me if you have any comments."
I-19	"The Stirling will find <u>specialized</u> applications where its attributes are outstanding and practically unattainable by conventional engines. It must be worth a <u>substantial</u> premium to warrant and bear the burden of the required extensive development of technology and infrastructure."
I-21	"I do not believe Stirling engines, or their derivatives, will ever find extensive commercial use. When a basic concept is 150 years old, and its theoretical advantages have been recognized for half that time, and there are no commercial applications in being-none at all-I believe there is something wrong with the concept. I believe that what is wrong is that it is essentially impossible to lubricate it adequately. One has the choice of gas lubrication, or of oil leaking

Code Number	
I-21 (cont)	into the heaters. Perhaps with sufficient effort, a solution can be found. Perhaps a helium/carbon system is possible. If so, it may have a use turning free heat into something useful, like cold. But I think there are many other more promising fields in which to work."
I-22	"I have serious doubts that heaters, regenerators and coolers can be optimized by substitution experiments as you propose. They must be optimized as part of the whole system. How will user find small output changes due to refinement of components? "Neither here nor in your IECEC paper do you discuss instrumentation or provisions for heat balances on components. How [do you plan] to determine conductivity losses, flow losses, end effects of heater, regenerator, and cooler, for instance."
I-23	"Your drive system should be of the Phillips hydraulic design such as used in their commercial cryogenic machines. The single crankshaft would be mounted below and drive two pistons at 120° - 150° vee angle. Each piston connecting rod is connected to a crank throw and shaft. The two collinear shafts are coupled by an epicyclic gear phase changer which permits phase angle to be changed continuously (rather than discretely) while running. This arrangement eliminates a pressurized crankcase and markedly reduces friction. In addition, Phillips has proven the practicability of this drive design."
I-29	"Our interest is primarily for consideration of a reasonably low cost and compact alternative to the internal combustion engine (particularly diesel) for applications where improvements in noise, emissions and multifuel capabilities would be important."
I-31	"I believe this laboratory engine will be very useful in developing a domestic body of knowledge on the Stirling engine."

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I-32	"The value of the engine you have described is: • useful for teaching institutions • doubtful for R&D organizations."
I-33	"We are not presently a manufacturer of engines. However, the corporation makes many components for engines, and therefore we are interested in the potential of the Stirling engine, and could consider a laboratory test engine at some time in the future to investigate component development."
I-35	"We do believe there is a need for a Stirling Research Engine because so little is known about Stirling engines. The reason why we don't think we would like to acquire one ourselves in that we have advanced research engines already in our test stands. These research engines are more optimized toward our own needs and where we believe the Stirling engine will find its first applications."
I-38	"Our organization does not have an active Stirling engine program. If we initiate such a program, it would almost surely be directed toward <u>controls</u> for the engine.
I-40	"I feel unqualified to make technical responses to your survey. I am curious about Stirling engines, however, and I do want a copy of the results of your survey."
I-42	"I believe that omission of smaller scale engines in your laboratory would restrict development and application of Stirling engines. There are numerous applications in Communications and Electronics which are practical for small scale (100W - 1 KW) energy converters. Widespread introduction of Stirling engines in this application would incentivize development and evolution to higher power levels. I also recommend more intense development of the free-piston Stirling engine in view of the self-evident advantages of simplicity and freedom from sealing problems and complex mechanical linkages required

Code Number	
I-42 (cont)	to extract power from kinematic-type engines. The free-piston design is inherently more reliable and manufacturable than the proposed engine."
I-43	"The object for most industrial organizations is to have a test vehicle which can do more than demonstrate Stirling concept works. It needs to be able to develop performance analyses, evaluate mechanical or operating level changes, and serve as a test bed to generate operating parameter data. Operating pressure level, for example, may be too limiting for range exploration."
I-46	"Although the Stirling engine has great potential, there are current problems with it (1) cost, (2) reliability of heater system, (3) hydrogen containment, and (4) control system. Fuels and lubricants have not been identified as a problem, and until the above problems have been solved, we believe it is premature to consider optimization of the fuel/lubrication system, if in fact this is needed even then."
I-47	"The Stirling engine has several advantages over current power sources. However, the main effort should be applied on manufacturing, cost, size and weight. Until these items are resolved along with universal reliability, the internal combustion engine will continue as our major source of power."
I-49	"We would be mostly interested in the effect of the Stirling engine on fuels and lubricants. Results obtained from a prototype test engine would probably not be useful in predicting the effect of a commercial Stirling engine on fuels or lubricants."
I-51	"1. We have manufactured a Stirling engine for exclusively educational use for more than a decade. The unit has a minimal power output (several watts) and is used for basic instruction at college level, primarily in Physics.

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I-51 (cont)	2. Important aspects for this role, also of interest in more advanced teaching situations (e.g. student labs in Engineering) are the versatility of the unit (prime mover, heat pump, refrigerator) and the 'didactic transparency' - i.e. the readiness with which the student can correlate instructional practice (in the units) with underlying thermodynamic theory.
	3. In educational practice, research units are generally too versatile, (and expensive), and often too sensitive to inexpert handling."
I-60	"We have received your interesting letter regarding the JPL Stirling engine activities. The interest of our organization is not oriented towards engine manufacturing, and we would therefore not be in a position to guide or recommend you of a possible extent and direction of your future work.
	We would like to encourage you in your Stirling development work, and agree with your technical positive comments regarding the hot-gas engine technology in general. If you plan to publish any further material on the development of the Stirling engine at JPL please keep us informed and put us on the mailing list."

APPENDIX D

Government Agencies

Code Number

G-1 "An engine capable of operating efficiently with inside heater wall temperature down to 400°F would be quite useful for system development of solar-thermal systems."

G-2 "My initial interest in Stirling engines came about as part of a study to evaluate solar thermal power generation using small heat engines (ex. Brayton or Stirling). The idea of providing a research engine for laboratory uses is an excellent one, and I'm sure would result in a large amount of valuable information. However, I can think of a major caveat.

The final engine configuration must be a flexible design, able to incorporate a very wide range of adaptations and even improvements, otherwise it becomes a "black box" which may stifle rather than promote Stirling engine understanding and development. I believe many academic institutions and laboratories would be interested in obtaining a Stirling research engine to modify and re-work to their needs and incorporate their improvements. I suggest that besides a questionnaire you hold a meeting of interested individuals (like at the ASME winter 1979 Annual Meeting) to discuss what modification capabilities they require. Please feel free to call on me for any help on this."

G-3 "To be most valuable to us, the SLRE needs to have modest weight (to permit mounting at the focus of a parabolic dish), a small profile (to avoid excessive blockage of parabolic dish surface), and the ability to operate well at lower than design hot temperature, as well as at design temperature. This would permit systems tests with parabolic trough or other collectors. Compatibility with a liquid metal heat pipe would be very helpful, but as a minimum, the ability to interface with a solar receiver should be incorporated."

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G-3 (cont)	Ability to interface with an automatic control system is also important. Operation at other than horizontal or vertical position would also be necessary for the solar application."
G-5	"I was interested in Stirling cycle engines (free piston types primarily) for space power applications in the 50-200 Kw range for a comparison study. The current program does not involve Stirling engines. However, I intend to follow development in general for possible future applications."
G-6	"Use of Stirling cycle engines for military vehicular propulsion is hampered by size and heat rejection. We do, however, have requirements for auxiliary power (silent watch) capability in the 10-20 KW range. Current developments are gas turbine. Stirling is a candidate for improved efficiency and reduced noise."
G-7	"The closed-loop Stirling engine might have use in future space missions. The development and testing of such a reliable light-weight system would involve us if nuclear heat sources are considered as the primary power."
G-11	"1. The point of view I express is that of headquarters located program manager. The opinions of personnel located in technology centers and laboratories will be different. 2. We see the possibilities of small engines (less than 100 horsepower) being used for total energy applications. The fuel for such engines, however, might well be petroleum based. 3. The success of the Stirling engine program will depend to a great extent on Federal funding and support."

Code Number

G-12 "We are interested mainly in low-power systems, of very high reliability, for generating electricity. Consequently we do not need rotation, and have been able to avoid the need for sliding surfaces by using a metal diaphragm instead of a piston, and by suspending the displacer on a stiff spring, out of contact with the cylinder wall. Consequently, our geometry is so different from that of the SLRE that we would not expect it to be very helpful in our work."

JET PROPULSION LABORATORY California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103

December 27, 1978

Refer to: 344S-78-186
344S-FH:bh

Dear

Stirling cycle engines can, in theory, attain the Carnot efficiency. This potential, coupled with low emissions and its ability to operate from a large variety of external heat sources, makes the Stirling cycle a challenge worthy of being pursued. Translating this potential into practical, competitively priced hardware is a challenge facing the engineering community.

When used in a prime mover role, applications particularly well suited for Stirling engines include the conversion of solar to electrical energy, silent power generation systems, a reliable power source for remote locations, underground and marine propulsion and the propulsion source for automobiles. Stirling cycle machines can also be used effectively as heat pumps and refrigeration devices. One of the major advantages of Stirling machines arises from the fact that the cycle uses an external source of energy. These sources include solar heat, nuclear heat, waste industrial heat, or any combustion device burning solid, liquid, or gaseous fuels.

The fundamental understanding of Stirling cycle engines principally resides within a limited number of European organizations. When compared to the Otto or Diesel cycle engine, the Stirling developmental state must be considered less mature. As one step in expanding the knowledge relative to and accelerating the development of Stirling engines, NASA, through the Jet Propulsion Laboratory (JPL), is sponsoring a program which will lead to a versatile Stirling Laboratory Research Engine (SLRE). An objective of this program is to lay the groundwork for a commercial version of this engine. It is important to consider, at an early stage in the engine's development, the needs of the potential users so that the SLRE can support the requirements of educators and researchers in academic, industrial, and government laboratories.

Telephone (213) 354-4321 Twx 910-588-3269 Twx 910-588-3294

The SLRE is envisioned as an experimental tool to be used for research purposes to support the development of a broad range of analytical modeling activities, for alternative fuels research, and to develop and evaluate new approaches to the design of components for Stirling engines. The expertise in Stirling cycle machines which presently resides within only a few organizations could in this way be expanded to others, and directed towards a variety of diverse, product-oriented applications. It is envisioned that the final configuration SLRE would be made available through a commercial source. Engine cost and Government incentives, if any, have yet to be determined but will be at least partially dependent on the market as developed by this survey and succeeding progress in the Stirling arena.

In order that the SLRE program be structured to support the above objectives, it is necessary to gain the best possible understanding of future needs of Stirling engine researchers for a laboratory engine. To this end we have enclosed a questionnaire and a reference set of engine parameters, (Attachment A), to facilitate your comments. It is being sent to heat engine researchers within industry, government, and academia. Survey results will be used primarily in the design of the commercial engine. We value your opinion and consider it important in attaining the best survey possible.

Specific objectives of this survey are as follows:

1. Assess the current interest of the technical community in Stirling engines and in the uses envisioned.

2. Determine the extent of interest in a commerically available laboratory research test engine.

3. For those interested in the laboratory engine concept, determine the key attributes desired.

The results of the questionnaire, Attachment B, will provide guidance in determining the extent and direction of future work on the SLRE project. Your help is solicited. Responses will not be identified as to origin unless you authorize us to do so, as indicated at the beginning of the questionnaire.

If you have any questions regarding this survey, please call Mr. Frank Hoehn (213) 354-6274 or Mr. Fred Vote (213) 354-4116. If FTS is available to you, the corresponding FTS numbers are 792-6274 or 792-4116.

Your response by February 16, 1979 would be appreciated.

Yours very truly,

Frank W. Hoehn

Frank W. Hoehn
Member Technical Staff

Attachments

SPECIFICATIONS FOR A REPRESENTATIVE STIRLING LABORATORY RESEARCH ENGINE (SLRE)

Design Horsepower @ 3000 rpm	12.2 hp (9.0 kw)
Cylinder Bore	2.865 in. (73.0 mm)
Piston Stroke	2.125 in. (53.8 mm)
Number of Crankshafts	2
Number of Cylinders	2
Phase Shift between Crankshafts	Variable
Swept Volume per Cylinder	13.79 in^3 (225.9 cc)
Swept Volume Ratio	1.00
Design Engine Speed	4000 rpm
Design Mean Pressure	68 atm (6900 kN/m^2)
Working Gas	Helium/Hydrogen
Heater Inside Wall Temperature (Design)	1400°F (760°C)
Cooler Inside Wall Temperature (Design)	100°F (38°C)
Number of Cooler Tubes/Cylinder	109
Number of Heater Tubes/Cylinder	18
Number of Regenerators per Cylinder	1
Regenerator Matrix Configuration	Parallel Plane-type
Total Dead Volume	23.5 in^3 (385.0 cc)
Dead Volume Ratio	1.7

Attachment A

REFERENCE ENGINE DESCRIPTION

A first generation SLRE has been designed, fabricated, and assembled for NASA at the Jet Propulsion Laboratory. The preprototype engine shown in the attached photograph is a horizontally-opposed, two-piston, single-acting Stirling machine with a dual-crankshaft drive mechanism.

The test engine is designed for maximum modularity and is assembled using an in-line arrangement to provide for the interchangeability of seals and heat exchanger components. An advantage of this arrangement is that the components are assembled with minimum dead volume,since no interconnecting external flow passages or ducts are required. Rated output power for the preprototype engine is 9 KW at 3000 rpm and 1000 psia base pressure using helium for the working fluid. The test engine is coupled to a universal dynamometer Typical test variables which can be studied include base pressure, working fluid type, phase angle, hot and cold gas temperature, and engine speed.

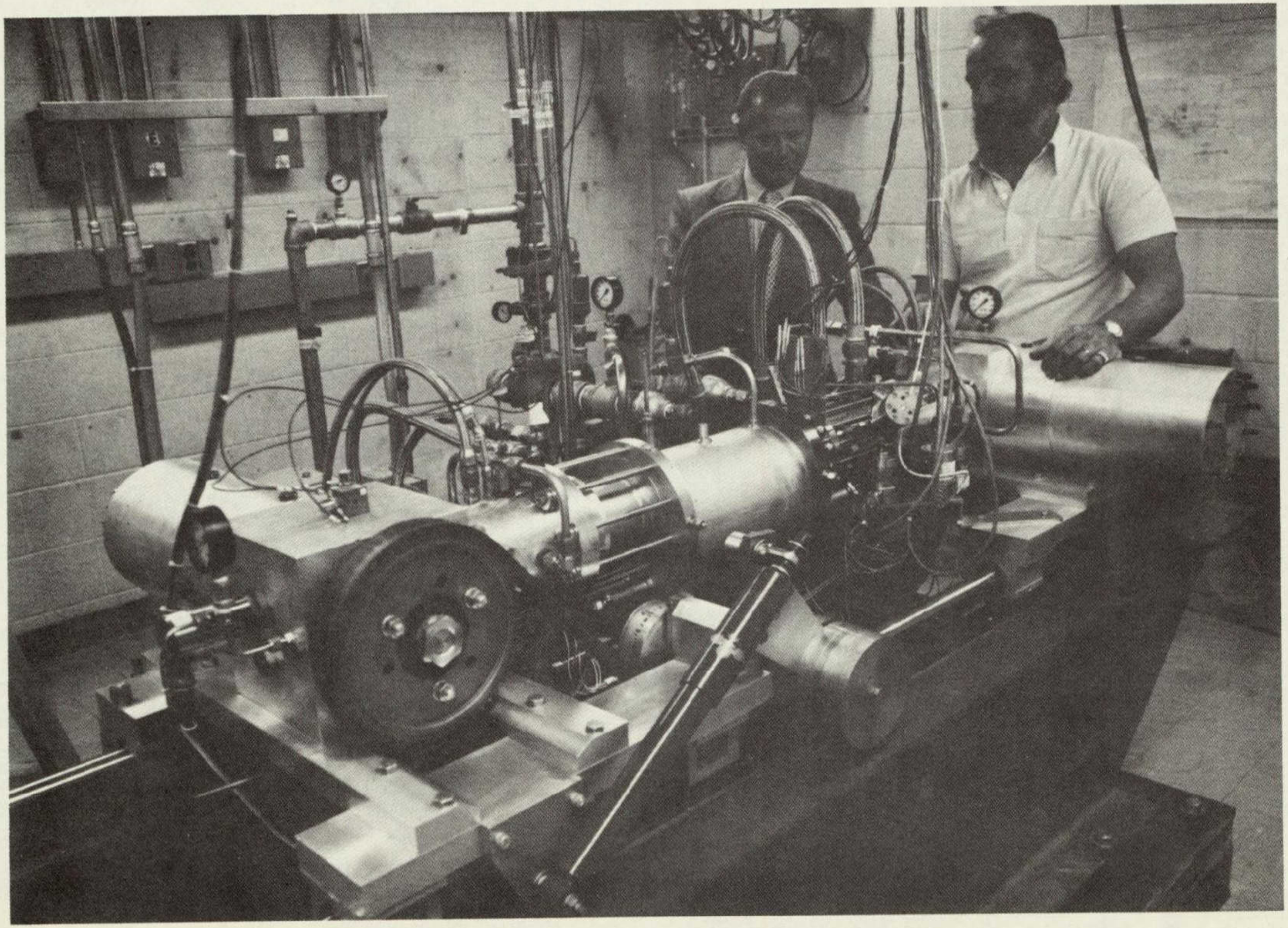
The cooler is a conventional cross-flow heat exchanger consisting of copper tubes and a stainless steel housing. An external source of cooling water is provided to maintain the desired cold side gas temperature. Standard calorimetric methods are used to experimentally determine the SLRE heat rejection rates. The heater for the preprototype SLRE is electrically powered to facilitate the measurement of total input energy.

The regenerator alternately stores and releases heat during the appropriate time in the Stirling Cycle. It also acts as a temperature barrier between the hot and cold space on the engine. The regenerator housing is machined from Inconel and contains a porous matrix which provides a large heat transfer surface, high heat capacity, low pressure drop and minimum internal volume.

The lubrication system consists of two separate but identical pump assemblies. Each pump contains a two-stage rotary gear mechanism, oil filter, storage tank, pressure regulation system and distribution system which supplies oil to the engine bearings and pressure-balanced face seal. Each lube pump bolts to one face of a crankcase and provides support for one of the crankshaft main bearings. The other main bearing is installed in the opposi side of the crankcase. The crankcases, which are designed to operate at the working pressure of the engine, are secured to sliding platforms and guided with linear ball bearings on a track. Timing belts are used to couple the engine flywheels to the dynamometer shaft. Phase angle control is achieved by changing the relative angular position of the two flywheels.

The engine technology and understanding of the thermodynamic cycle which will result from this program will be applicable to a wide range of applications. The modular approach used in the design permits complete flexibility in substituting alternate components having different specifications. Details of this first generation engine are identified in the following Table.

STIRLING LABORATORY RESEARCH ENGINE



QUESTIONNAIRE

REGARDING THE POSSIBLE NEED FOR AND THE CHARACTERISTICS OF A STIRLING RESEARCH ENGINE FOR LABORATORY USES

A. General Information

1. From what perspective are you responding?

   Academic ☐ Governmental ☐

   Industrial ☐ Other ☐

   If "other," please explain: ____________________

   ____

2. Please provide us with the following information for evaluation and follow-up of the questionnaires:

   Your Name: ____________________

   Address: ____________________

   Function or Title: ____________________

   Type of Organization: ____________________

   Telephone: ____________________ Commercial ☐ FTS ☐

3. May we identify you in reports to be published which contain results from and analyses of this questionnaire?

   Yes ☐ No ☐

4. Would you be interested in obtaining results of this questionnaire?

   Yes ☐ No ☐

5. Is there another office or individual elsewhere in your organization which may have an interest in the engine described?

   Yes ☐ No ☐

   If "yes", please identify:

   Name: ____________________

   Address: ____________________

   Function or Title: ____________________

   Type of Organization: ____________________

13. What engine size is of interest to your organization?

Under 10KW ☐ 10-50KW ☐ 50-200KW ☐ Other ☐

If other, please indicate specific size planned:

____

14. What uses of the SLRE would be of interest to your organizaton?

Teaching Aid ☐ Component Development ☐ Analytical Models ☐

Demonstration ☐ Systems Development ☐ Fuels Research ☐ Other ☐

If "other", please explain: ____________________

____

15. What types of heat sources could be used to power a research engine in your laboratory?

Solar ☐ Electric ☐ Combustor ☐ Other ☐

If "other", please explain: ____________________

____

C. The questions below are directed more to you as a professional individual than as a representative of an organization.

1. What special characteristics of Stirling engines do you expect to find most advantageous for end-use?

High thermal efficiency ☐ Low emissions ☐ Low noise levels ☐

Multi-fuel capability ☐ Other ☐

If "other, please describe: ____________________

____

2. What end uses for Stirling engines do you expect to become commercially viable in the near (1980-1990) term?

Solar to Electrical Energy Conversion ☐
Automotive Use ☐
Other Surface Transportation ☐
Underground Propulsion ☐
Air Conditioning/Refrigeration ☐
Other ☐

If "other", please describe: ____________________

____

3. What end uses for Stirling engines do you expect to become viable beyond 1990?

   Solar to Electrical Energy Conversion ☐
   Ground Transportation Propulsion ☐
   Underground Propulsion ☐
   Air Conditioning/Refrigeration ☐
   Other ☐

   If "other", please describe:______________________________

   ____

4. I would like to make the following comments to aid NASA/JPL in assessing my response: